Cuadernos de Investigación Geográfica *Geographical Research Letters*	2026	Nº xx (x)	pp. xxx-xxx	EISSN 1697-9540

Copyright © 2026, The authors. This work is licensed under a Creative Commons Attribution 4.0 International License.

http://doi.org/10.18172/cig.7276

SEASONAL ANALYSIS AND QUANTIFICATION OF SAND DUNE DYNAMICS IN THE TERNATA OASIS (MIDDLE DRAA, MOROCCO) USING TOPOGRAPHIC SURVEYS AND GIS

MAHJOUB BENBIH [1]*, ABDERRAHMAN OUAMMOU [1], M'HAMED NMISS [2], HASSAN NAIT SI [1], ABDELFATTAH BEN KACEM [3]

[1] Ibn Zohr University, Faculty of Letters and Human Sciences, Department of Geography, Agadir, Morocco.

[2] Hassan II University, Faculty of Letters and Human Sciences, Department of Geography, Mohammedia, Morocco.

[3] Sidi Mohamed Ben Abdellah University, Faculty of Letters and Human Sciences, Department of Geography - Fez-Sais, Morocco.

ABSTRACT. This study focuses on the seasonal analysis and quantification of the morpho-sedimentary dynamics of transverse dunes in the Ternata oasis (Morocco) It is based on an integrated methodological approach that combines topographic surveys conducted using a LEICA TS 02 total station, along with spatio-temporal data processing and analysis using GIS software. The primary objective was to monitor the morphological evolution of the dunes over the four seasons of the year 2023. Descriptive and cartographic approaches also contributed to refining the understanding of the internal dynamics of these aeolian forms. The results highlighted a general trend toward accumulation, evidenced by a notable increase in the volume and surface area of the two dunes analyzed. Regarding dune mobility, the topographic measurements revealed differentiated displacements depending on the orientation of dominant winds and local topographic constraints. These spatial and directional divergences underscore the combined influence of wind regimes, geographic positioning, and the geometric characteristics specific to each dune. Moreover, the seasonal analysis revealed a contrasting dynamic marked by strong morpho-sedimentary variability. Dune nº 1 displayed an unstable evolution, with a significant volumetric increase until summer, followed by a sharp decline in autumn—reflecting an alternation between dominant erosional phases (spring–summer) and accumulation phases (autumn). Dune nº 2, on the other hand, exhibited a more extreme dynamic, with a volumetric peak in summer that is rapidly reversed in autumn, indicating its heightened sensitivity to wind activity.

Análisis estacional y cuantificación de la dinámica de dunas arenosas en el oasis de Ternata (Drâa Medio, Marruecos) a partir de levantamientos topográficos y sistemas de información geográfica (SIG)

RESUMEN. Este estudio se centra en el análisis estacional y la cuantificación de la dinámica morfosedimentaria de las dunas transversales en el oasis de Ternata (Marruecos). El análisis se basa en un enfoque metodológico integrado que combina levantamientos topográficos realizados mediante una estación total LEICA TS 02, junto con el tratamiento y análisis espaciotemporal de los datos utilizando SIG. El objetivo principal fue el seguimiento de la evolución morfológica de las dunas a lo largo de las cuatro estaciones del año 2023. Los enfoques descriptivo y cartográfico contribuyeron igualmente a profundizar en la comprensión de la dinámica interna de estas formas eólicas. Los resultados ponen de manifiesto una tendencia general hacia la acumulación, evidenciada por un aumento significativo del volumen y de la superficie de las dos dunas analizadas. En cuanto a la movilidad dunar, las mediciones topográficas revelaron desplazamientos diferenciados en función de la orientación de los vientos

Articulo Aceptado / Paper Accepted

dominantes y de las restricciones topográficas locales. Estas divergencias espaciales y direccionales subrayan la influencia combinada de los regímenes de viento, la posición geográfica y las características geométricas propias de cada duna. Asimismo, el análisis estacional revela una dinámica contrastada marcada por una fuerte variabilidad morfosedimentaria. La duna nº 1 presentó una evolución inestable, con un incremento volumétrico significativo hasta el verano, seguido de un descenso acusado en otoño, lo que refleja una alternancia entre fases erosivas dominantes (primavera–verano) y fases de acumulación (otoño). Por su parte, la duna nº 2 mostró una dinámica más extrema, con un máximo volumétrico en verano que se revirtió rápidamente en otoño, lo que indica una elevada sensibilidad a la actividad eólica.

Key words: aeolian dynamics, topographic surveys, GIS, seasonal analysis, Ternata Oasis.

Palabras clave: dinámica eólica, levantamientos topográficos, SIG, análisis estacional, Oasis de Ternata.

***Corresponding author:** Mahjoub Benbih, Ibn Zohr University, Faculty of Letters and Human Sciences, Department of Geography, Agadir, Morocco, Mahjoub.benbih@edu.uiz.ac.ma

Received: 22 February 2026

Accepted: 1 July 2026

Articulo Aceptado / Paper Accepted

1. Introduction

In Morocco, as in other North African countries, wind dynamics represent a major environmental challenge, compromising both soil fertility and the sustainability of economic activities (Benbih *et al.*, 2025a), particularly in the arid and semi-arid regions of the southeast. Approximately 250,000 ha of land in these areas are threatened by sand encroachment, both along the Atlantic coasts and in inland regions such as the Drâa and Tafilalet, where the intensity of aeolian processes is exacerbated by climatic and anthropogenic factors (FAO, 1986).

Recent studies estimate that nearly 15,000 ha of oasis zones in southeastern Morocco are already covered by sand, while similarly sized areas remain severely exposed to this phenomenon (FAO, 2016). This dune encroachment results in an alarming retreat of agricultural lands, jeopardizing the food security of local populations. The oases of the Drâa and Tafilalet experience an estimated annual loss of 500 ha of arable land due to progressive sand encroachment, highlighting the growing pressure on local natural resources (Ait Hamza *et al.*, 2010).

Today, Moroccan oasis systems, particularly those of the Middle Drâa Valley, are undergoing severe degradation, resulting from a complex interplay of climate change impacts, demographic pressures, and accelerating urbanization (Ait Hamza *et al.*, 2010; Benbih *et al.*, 2023; Benbih *et al.*, 2026; Beraaouz *et al.*, 2019; Moumane *et al.*, 2022). In this concerning context, a deeper understanding of the mechanisms governing wind dynamics in the arid oasis environments of southeastern Morocco becomes essential. The present study adopts a geomorphological approach aimed at analyzing the processes of formation, evolution, and impact of dune forms on oasis ecosystems.

Dunes have long attracted the interest of travelers and explorers, and later of planners and researchers, especially since the 19th century (Callot and Crépy, 2018). However, the understanding of the mechanisms related to their genesis, morphological evolution, and displacement dynamics initially proved complex due to the lack of appropriate observation and investigation methods. The scientific study of aeolian dynamics and dune forms truly gained momentum with the foundational works of Bagnold (1941), followed by those of Fryberger (1979), McKee (1979), Tsoar (1984), Ungar and Haff (1987), McEwan (1993), McKenna Neuman and Nickling (1994), Lancaster (1995), Livingstone and Warren (1996) and Goudie *et al.* (1999). These contributions laid the conceptual and experimental foundations for analyzing wind-related processes in desert environments. Today, this approach has been

significantly enhanced through the integration of geospatial technologies, such as satellite imagery and remote sensing (Adesina *et al.*, 2024; Anthony *et al.*, 2021; Benbih *et al.*, 2025b; Bijaber *et al.*, 2024; Nmiss *et al.*, 2025a, 2025b; Rahman, 2025), which allow for continuous, multi-scale, and high-resolution observation of arid landscapes (Atiki *et al.*, 2021; El-Bouhali *et al.*, 2024). The widespread availability of satellite images with resolutions equal to or less than 10 meters has greatly facilitated the mapping and spatio-temporal analysis of dune systems (Aydda *et al.*, 2020; Benbih *et al.*, 2025c; Elbelrhiti, 2011; Nmiss *et al.*, 2025a, 2025b).

This study focuses on active dune forms, composed of loose and unconsolidated sands (Cailleux and Tricart, 1959), which reflect a high aeolian transport potential. These forms, mainly transverse dunes, are characterized by the high mobility of their sandy material. The primary objective of this research is to monitor, analyze, and quantify the seasonal dynamics of sand dunes in the Ternata oasis, with a particular focus on the spatio-temporal variations in their mobility and morphology. A spatialized database will be developed, incorporating measurements of transported sand mass. This database will provide an accurate environmental assessment of the site and serve as a decision-support tool for planners and land managers. The findings are expected to guide sustainable management strategies and risk prevention measures related to sand encroachment in this region, which is particularly vulnerable to global changes.

2. Study Area

Ternata is situated in the upper reaches of the Middle Drâa basin, on the left bank of the Drâa River. It lies east of the villages of Boukhlal and Zaouiat El Hana, and downstream of the Tinzoulin oasis, between latitudes 21°30′ and 23°30′ north, and longitudes 5°47′ and 5°43′ west. Covering an area of approximately 500 ha, the site benefits from relatively easy access due to its proximity to the city of Zagora (less than 20 km), thereby enhancing its economic and touristic significance (Fig. 1).

From a morphological standpoint, Ternata is predominantly characterized by transverse sand dunes, whose lengths range between 130 and 310 meters. These dunes generally align along a west-southwest to east-northeast orientation (Benbih *et al.*, 2022). The spatial clustering of these dunes can be attributed to the site's distinctive topography, which is enclosed by three main morphological units acting as orographic traps. This setting facilitates the accumulation and stabilization of sandy sediments (Benbih, 2025).

Meteorological data recorded at the Zagora station during the period 1989–2010, located within the oasis environment, reveal a marked seasonal and interannual variability in mean wind speed. Annual mean wind speeds generally ranged between 1.3 and 2.3 km/h, with the highest annual mean value recorded in 1990 (2.30 km/h) and the lowest in 1997 (1.32 km/h). Seasonally, the windiest period extends from April to June, during which mean wind speeds vary between 2.0 and 3.8 km/h, reflecting the enhanced atmospheric instability that characterizes late spring and early summer. In contrast, the lowest wind activity occurs from October to December, when mean wind speeds range from 0.6 to 1.6 km/h. At the monthly scale, May consistently exhibits the highest mean wind speeds (2.0–3.1 km/h, reaching 3.83 km/h in some years), whereas December records the lowest values (0.7–1.5 km/h). These seasonal variations are mainly associated with changes in regional atmospheric circulation and the influence of Saharan air masses on southern Morocco (Karmaoui *et al.*, 2014). It should be noted that the meteorological station is situated within the oasis, where dense palm groves and cultivated areas locally reduce near-surface wind velocity; therefore, the recorded values primarily characterize the oasis microclimate rather than the wind conditions prevailing over the surrounding open desert.

Articulo Aceptado / Paper Accepted

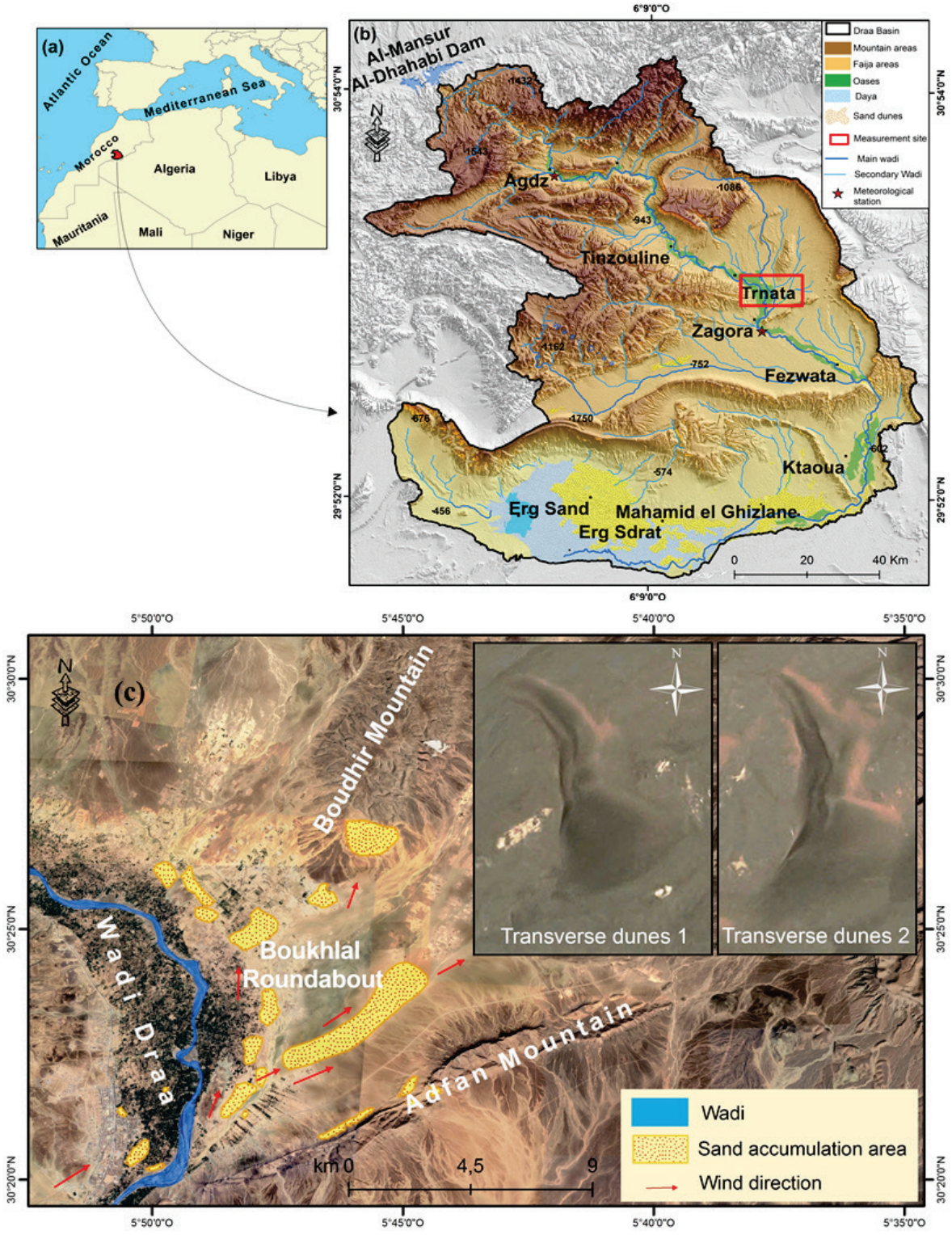

Figure 1. (a) Geographical location of Morocco within the Mediterranean Basin. (b) Study area (Faijal: alluvial depression; Daya: temporarily inundated closed depression). The red inset corresponds to the specific location of the measurement site (c).

Articulo Aceptado / Paper Accepted

Regarding wind direction, Bentaleb (2008) reports seasonal variability as follows:

- Autumn: prevailing winds from the northeast (NE) and north (N), with less frequent winds from the east (E) and northwest (NW).
- Winter: dominance of northwest (NW) and west (W) winds.
- Spring: alternation between northeast (NE) and northwest (NW) winds, accompanied by moderate occurrences of southeast (SE) and southwest (SW) winds.
- Summer: marked wind activity from the north (N) and south (S).

Finally, concerning the frequency of strong winds, a gradual decrease is observed from the northern to the southern parts of the Drâa basin: Ouarzazate exhibits a frequency of 10%, Zagora 20%, and Tagnite 18%. This pattern reflects an intensification of wind activity in downstream areas, linked to specific climatic conditions such as sandstorms and seasonal winds, which play a crucial role in aeolian sediment transport and dune formation (Bentaleb, 2008). The threshold for effective wind-driven sediment transport is 7 m/s.

3. Materials and methods

The study of the dynamics of transverse dunes was based on a methodological approach that combined several complementary strategies.

3.1 Selection of Representative transverse dunes

The selection of two transverse dunes located in the Ternata area was made following a preliminary survey via Google Earth Pro and fieldwork. This choice was based on criteria such as spatial proximity and accessibility, inclusion within the same dune system, exposure to the same wind regime, and the relative distance from anthropogenic impacts.

3.2 Quantitative approach

The morphological changes in the dunes were assessed using a topographic surveying device that allows the measurement of their geometric dimensions (length, width, height, length of the right horn, length of the left horn, as well as the longitudinal axis of the dune). The topographic survey was conducted by establishing a coordinate mesh for each point (X, Y, Z).

3.2.1 Topographic survey protocol

The topographic survey was carried out using a LEICA TS 02 Total Station, with the aim of measuring the geometric dimensions of the dunes and monitoring their morphological and sedimentary evolution (in terms of volume) (Fig. 2). It is important to note that this monitoring operation spanned four seasons throughout the year 2023, with data collected in March (spring), June (summer), October (autumn), and December (winter). The measurement process is associated with a margin of error not exceeding 5 cm, which is mainly attributed to the nature of the study area (sandy environment). In addition, the instrumental accuracy of the device is specified at 1.3 mm in the X, Y, and Z coordinates.

Articulo Aceptado / Paper Accepted

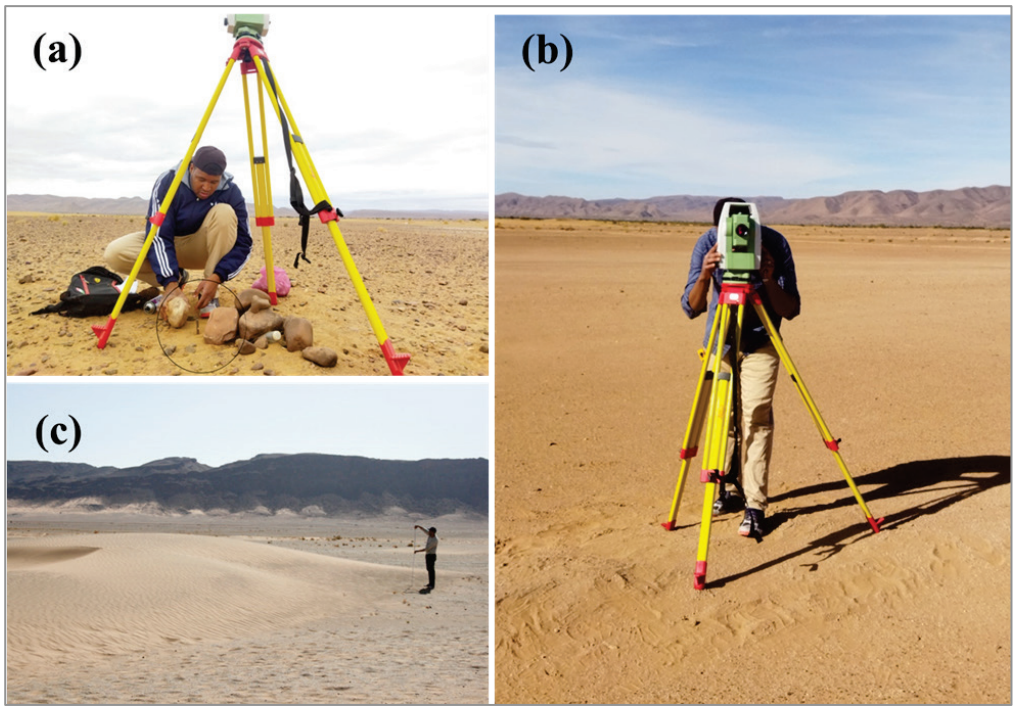

Figure 2. The methodological approach adopted in this study to quantify dune dynamics. (a) Installation of reference points. (b) Topographic survey. (c) Dune measurement. Date: 11/12/2022.

3.2.2 Data processing and analysis

This stage involved the creation of a database compiling information related to the physiographic, morphological, and volumetric changes of the studied dunes during all observation periods. The processing and correction of the data were performed using COVADIS, QGIS, and ArcGIS software.

3.3 Descriptive and analytical approach

The descriptive approach enabled the provision of both a general description of the dunes (location of the dune within the sandy unit) and a specific one, and was followed by the analysis of the collected data.

3.4 Cartographic approach

A cartographic approach was adopted to process, analyze, and represent the spatial data using COVADIS, QGIS, and ArcGIS software. The integration of these software was designed to capitalize on their complementary capabilities throughout the geospatial data processing chain. COVADIS was employed for the preprocessing and correction of field survey data, QGIS for data management and quality control, and ArcGIS for advanced spatial analyses and the generation of final cartographic products. All cartographic processing associated with this phase of the study was undertaken in 2023.

4. Results

4.1. Morphological and sedimentary evolution of transverse dunes in 2023

The transverse dunes monitored throughout the different observation periods in 2023 exhibited notable morphological, sedimentary, and surface changes.

Articulo Aceptado / Paper Accepted

In the case of transverse dune nº 1, the volume increased from 411.75 m³ at the beginning of the observation period to 610.11 m³ at the end, representing a total gain of 198.36 m³, with an average seasonal increase of 49.59 m³. The dune's surface area also expanded significantly, growing from 1,307.99 m² to over 1,577 m², i.e., a net increase of 269.01 m² (Fig. 3a and 4a).

Compared to the first dune, transverse dune nº 2 showed a more moderate evolution. Its volume rose from 892.25 m³ to 970.20 m³, reflecting a total increase of 77.95 m³. This volumetric evolution was accompanied by an expansion of the dune's surface area, which increased from 1,495.37 m² to 1,662.64 m², corresponding to a net gain of 167.27 m² (Fig. 3b and 4b).

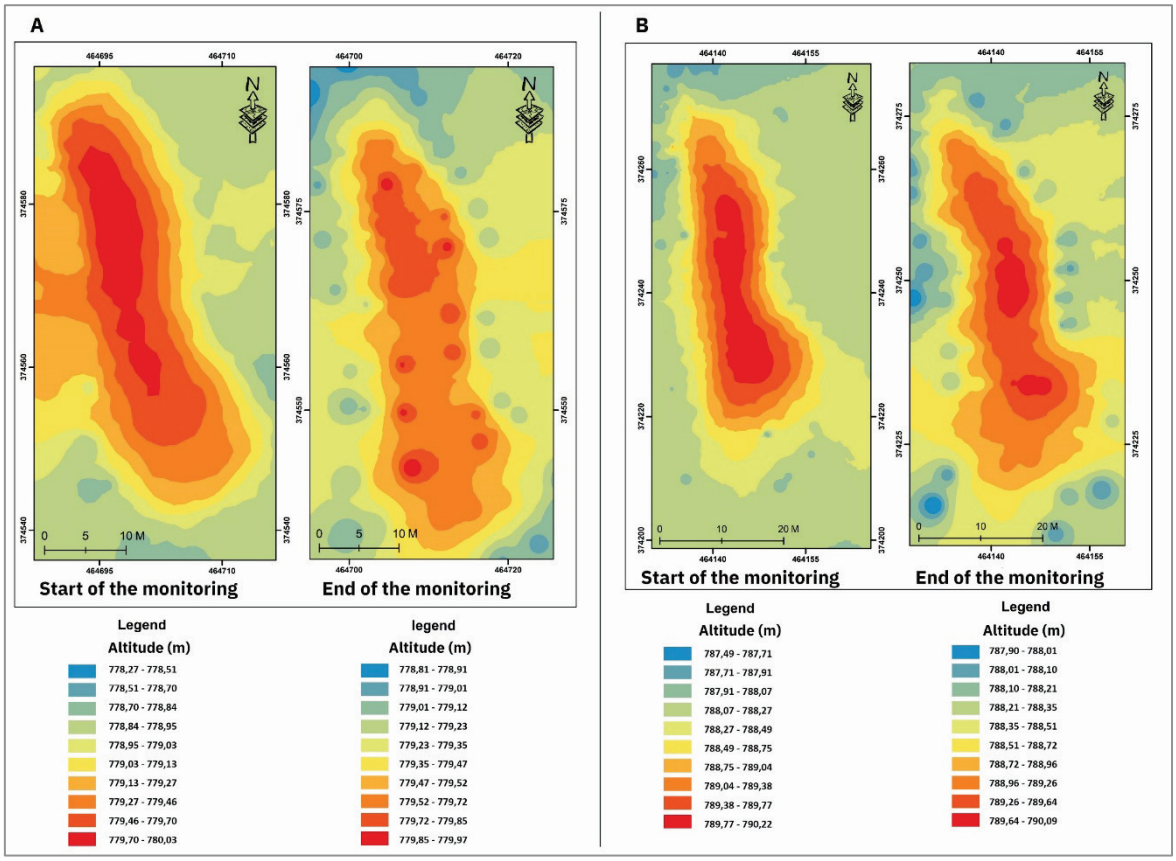

Figure 3. Morpho-dynamic evolution of transverse dune nº 1 (a) and nº 2 (b) from the start to the end of the monitoring period 2023.

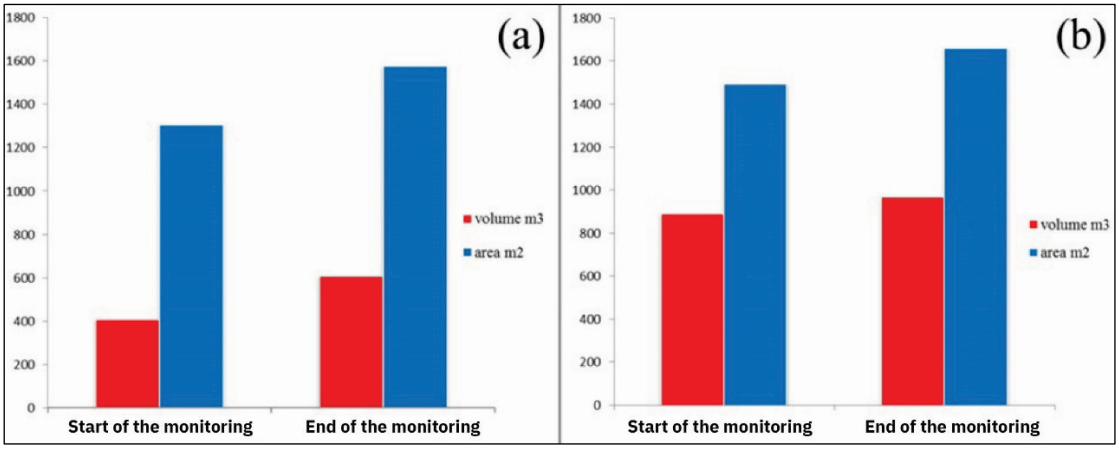

Figure 4. Morpho-sedimentary dynamics - volumetric and areal distribution of erosion and accumulation- for transverse dune nº 1 (a) and nº 2 (b) from the start to the end of the monitoring period 2023.

Articulo Aceptado / Paper Accepted

4.2. Mobility of transverse dunes in 2023

The studied dunes exhibited, during the observation periods, a significant dynamic behavior that varied according to their geographical position and geometric characteristics.

The mobility of the transverse dunes revealed a marked movement in two opposite directions: the first, from northwest to southeast (dune nº 1), and the second, from southeast to northwest (dune nº 2). This directional divergence highlights the critical role of the wind regime in the formation and evolution of these dune forms. The divergence is attributed to the influence of local winds, the size of the dunes, and their position between three orographic barriers acting as sand traps. Furthermore, the particular position of dune nº1, located within the bed of Oued El Fargh, makes it more exposed to wind action compared to dune nº 2, which is situated more centrally within the transverse dune field.

The average mobility of the two dunes, measured at their central sections, reached 3.83 m, compared to 7.57 m in their northwestern sections and 9.19 m in their southeastern sections (Table 1). More specifically, the average mobility of transverse dune nº 1 was measured at 5.90 m in the central section, 9.14 m in the northwest, and up to 15.18 m in the southeast (Fig. 5a). In contrast, the average mobility of dune nº 2 was recorded at 1.76 m in the central section, 6.37 m in the northwest, and 3.20 m in the southeast (Fig. 5b).

Table 1. Annual average rate of transverse dune mobility in Tranata region.

	Northwest Section (m)	Central Section (m)	Southeast Section (m)
Transverse dune nº 1	9.14	5.9	15.18
Transverse dune nº2	6.37	1.76	3.2
Average	7.57	3.83	9.19

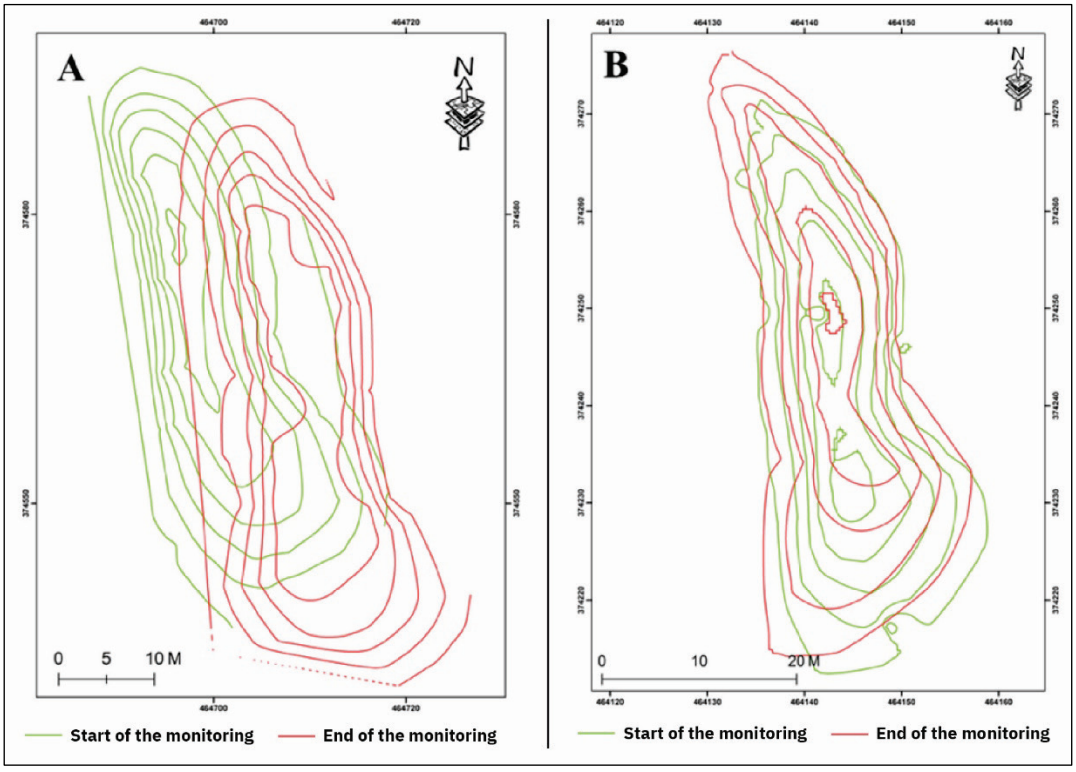

Figure 5. Mobility for transverse dune n° 1 (a) and n° 2 (b) from the start (green) to the end (brown) of the monitoring period 2023. Isolines represent contour lines connecting points of equal elevation.

Articulo Aceptado / Paper Accepted

4.3. Seasonal variations in the morphology of transverse dunes

The seasonal monitoring focused on measuring the geometrical dimensions of the dunes: length, width, and the width of both western and eastern flanks. The study also allowed for the calculation of total volume and occupied surface area, as well as the volumes and surfaces affected by erosion and sedimentation.

Transverse dune nº 1

During winter 2023, transverse dune nº 1 measured approximately 55.16 m in length and 13.31 m in width. The width of the western flank reached 13.58 m, while that of the eastern flank was 18.35 m. The estimated volume was 411.75 m³, over a surface area of 1,308 m², with erosion accounting for 54.25% and accumulation for 45.75% (Fig. 6 and 8a).

In spring, unlike in winter, the dune's length decreased to 52.5 m, while the width increased to 14.65 m. The western flank measured 14.37 m, compared to 17.29 m for the eastern flank. This corresponds to a reduction in length by approximately 2.66 m and an increase in width by 1.34 m, indicating a dispersal of the dune form. The dune's volume increased by 198.36 m³, reaching a total of 610.11 m³, over a surface of 1,577.79 m². During this period, erosion represented 87.01%, while accumulation dropped to 12.99% (Fig. 6 and 8a).

In summer, the dune extended to 59.69 m in length and 15.9 m in width. The western flank measured 13.53 m, and the eastern flank expanded to 21.53 m. The total volume reached 928.06 m³, across a surface area of 1,765.18 m², with erosion contributing 90.81%, and accumulation 9.19% (Fig. 6 and 8a).

In autumn, the dune reached a length of 63.04 m, with a width of approximately 16.06 m. The western flank measured 14.58 m, and the eastern flank 21.8 m. The volume was estimated at 310.00 m³, over a surface area of 1,209.70 m², with erosion accounting for 39.39%, and accumulation rising to 60.61% (Fig. 6 and 8a).

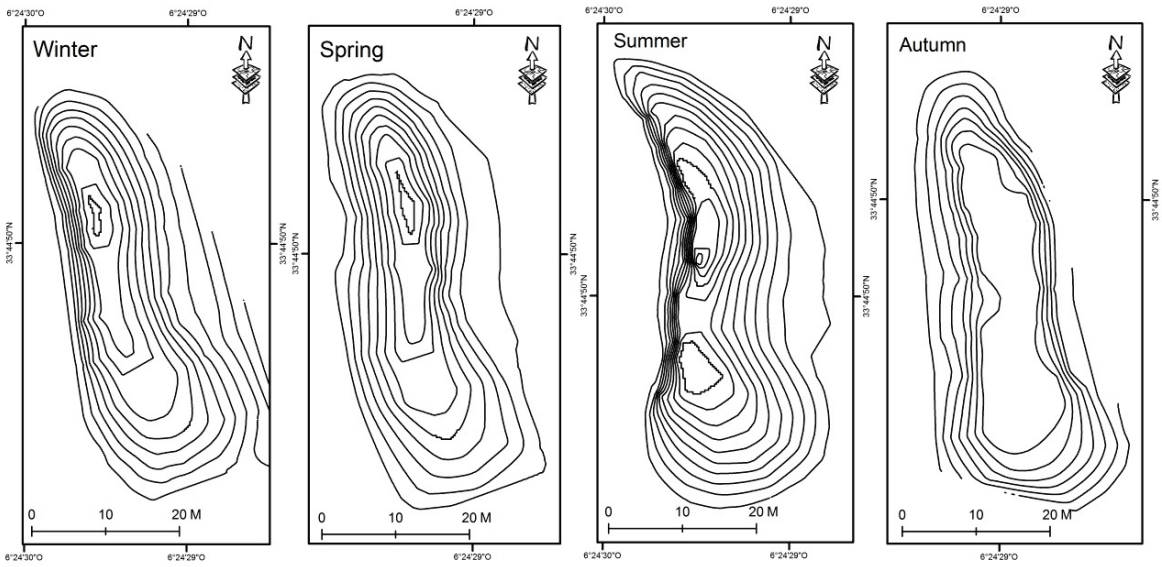

Figure 6. Seasonal morphological changes of transverse dune nº 1. Isolines represent elevation contours (m) derived from the total station topographic survey data.

Articulo Aceptado / Paper Accepted

Transverse dune nº 2

During the winter season, transverse dune nº 2 measured 64.3 m in length and 15.91 m in width. The western flank reached a width of 17.9 m, while the eastern flank extended to 23.24 m. Its total volume was estimated at 892.25 m³, over a surface area of 1,495.374 m². The erosion rate accounted for 72.08%, while accumulation represented 27.92% (Fig. 7 and 8b).

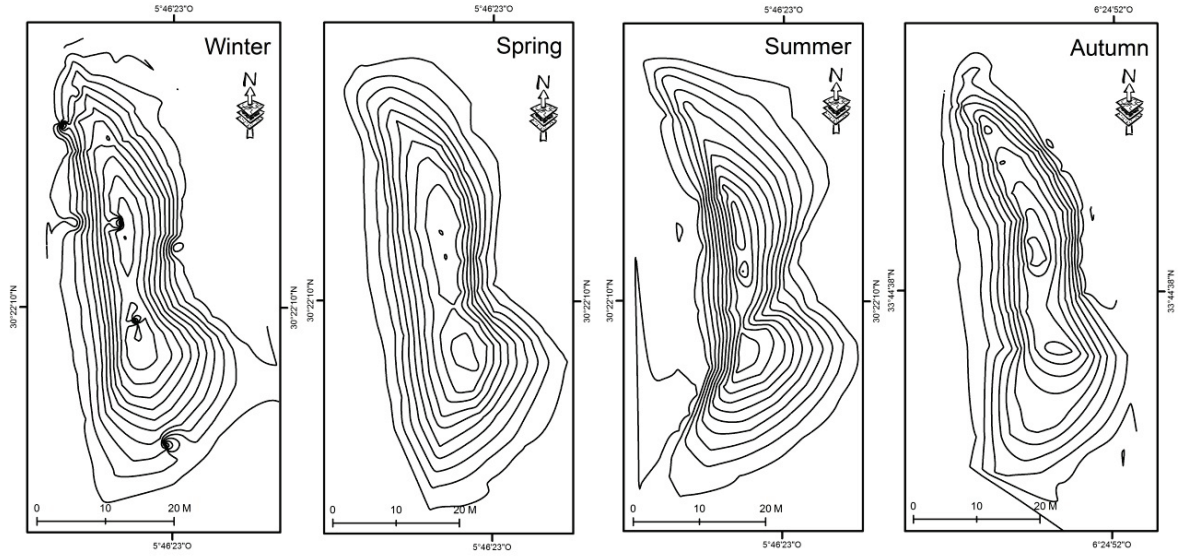

Figure 7. Seasonal morphological changes of transverse dune nº 2. Isolines represent elevation contours (m) derived from total station topographic survey data.

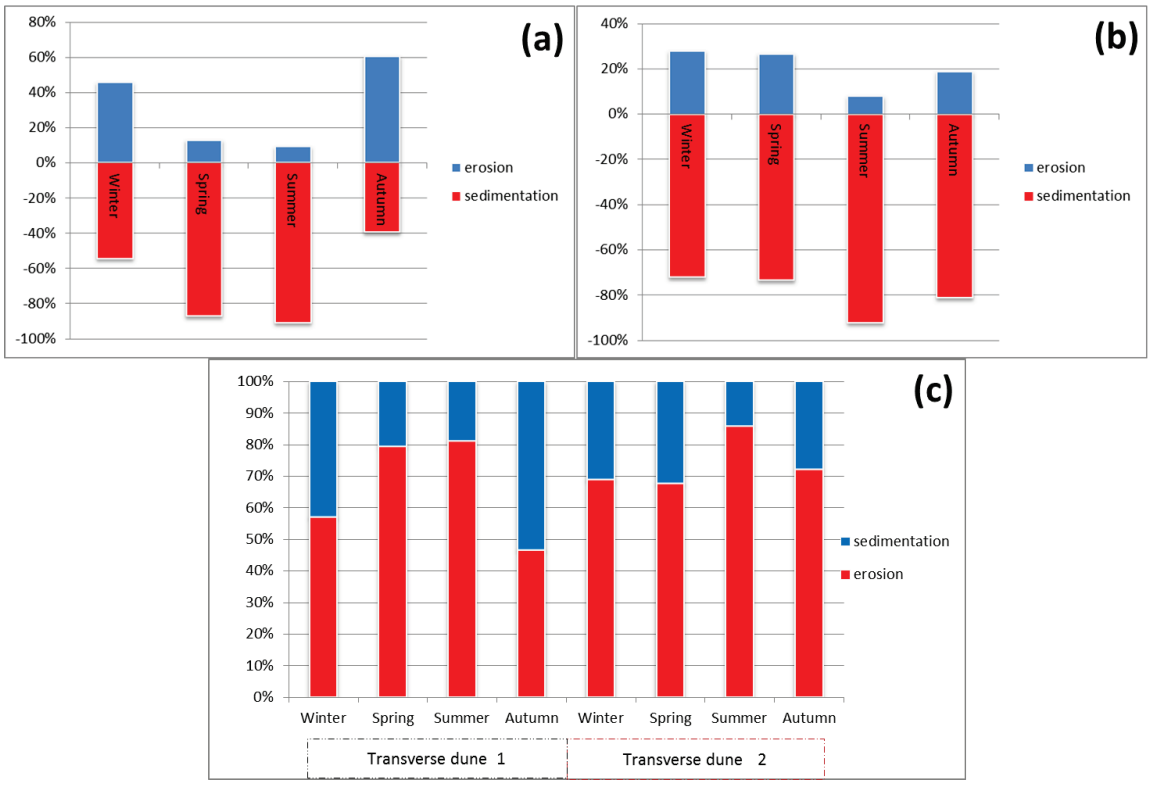

Figure 8. Erosion and accumulation volume in transverse dune nº 1 (a) and transverse dune nº 2 (b). Comparison between transverse dunes 1and 2 (c).

Articulo Aceptado / Paper Accepted

In spring 2023, the dune measured 63.03 m in length and 17.98 m in width. The western flank was 19.2 m wide and the eastern flank 25.33 m. In terms of sediment dynamics, the volume did not exceed 700.75 m³, spread over a surface area of 1,269.15 m², with erosion estimated at 73.37% and accumulation at 26.63% (Fig. 7 and 8b).

During summer 2023, the dune reached a length of 65.65 m and a width of 15.22 m. The western flank measured 19.8 m, while the eastern flank was 22.64 m wide. The recorded volume was 2,143.37 m³, over a surface area of 2,538.83 m², with a very high erosion rate of 92.17%, compared to only 7.83% for accumulation (Fig. 7 and 8b).

In contrast to the summer season, in autumn, the dune measured 67.03 m in length and 15.91 m in width. The western flank extended to 16.39 m, and the eastern flank to 22.69 m. The volume did not exceed 970.12 m³, over an area of 1,662.65 m², marking a notable decrease of 1,173 m³ compared to the summer. The erosion rate was 81.16%, while accumulation accounted for 18.84% (Fig. 7 and 8b).

5. Discussion

Based on the results of the topographic analysis of the transverse dunes in Ternata, transverse dune nº 1 experienced a well-marked seasonal dynamic throughout the year 2023. In winter, the dune had a volume of 411.75 m³, with an accumulation rate of 54.25%, which exceeded the erosion rate of 45.75%, indicating a phase of sediment gain. In spring, although the dune's length decreased, its volume increased to 610.11 m³, suggesting a phenomenon of lateral dispersion associated with surface expansion. This trend aligns with the findings of Bristow *et al.* (2000) and Wiggs (2001) who observed that an increase in dune volume may result from lateral expansion, even in an erosive context. However, this period was also marked by a strong intensification of erosive processes, accounting for 87.01% of the morphological dynamics. In summer, the dune reached its maximum volume of 928.06 m³, under conditions of clear erosion dominance (90.81%), reflecting pronounced instability. This dynamic supports the work of Tsoar (2001) and Kocurek and Ewing (2005), who emphasized that intense aeolian regimes during the hot season enhance dune mobility and increase their morphological instability. In autumn, the dune's volume decreased to 310 m³, while the accumulation rate rose again to 60.61%, surpassing the erosion rate (39.39%) and indicating a temporary return to a phase of sediment reconstruction. This observation is consistent with Lancaster (1995), who noted that calmer seasons—especially autumn and winter—are conducive to aeolian accumulation.

As for transverse dune nº 2, the results indicate a morphological dynamic strongly dominated by erosion throughout 2023. In winter, its volume was 892.25 m³, with a high erosion rate of 72.08%, reflecting substantial sediment loss. In spring, the volume decreased to 700.75 m³, while the erosion rate remained relatively stable at 73.37%, indicating the persistence of erosive processes. In summer, the dune underwent significant expansion, reaching a peak volume of 2,143.37 m³, despite a very high erosion rate of 92.17%. This situation may be explained, as suggested by Livingstone and Warren (1996) and Goudie *et al.* (1999), by a massive sediment influx followed by rapid redistribution under the influence of strong winds. In autumn, the dune's volume decreased again to 970.12 m³, accompanied by a slight reduction in the erosion rate to 81.16%, indicating ongoing erosion, albeit with moderately reduced intensity.

Despite seasonal variations in the geometric dimensions of the dunes, both total volume and relative erosion rates show broadly similar trends (Fig. 8c). Notably, the summer period is characterized by intense erosive activity, while the winter and autumn seasons are marked by lower erosion rates and a relatively higher accumulation rate in autumn compared to spring. These results corroborate the findings of Livingstone and Warren (1996), who stressed the key role of seasonal variability in the aeolian regime in shaping dune field dynamics.

Articulo Aceptado / Paper Accepted

This dynamic highlights the decisive influence of seasonal variations in the wind regime on the morphological evolution of transverse dunes by modulating erosion and accumulation processes. As Kocurek and Ewing (2005) pointed out, wind seasonality affects not only the intensity of erosion but also the direction and orientation of sediment flows. Erosion tends to dominate in spring and summer, while accumulation becomes more intense in winter and autumn. However, an increase in dune volume does not necessarily reflect a net accumulation phase—a phenomenon previously highlighted by Bristow *et al.* (2000) and Wiggs (2001) who noted that lateral dispersion can mislead traditional volumetric interpretations.

These results indicate that the morpho-sedimentary trend of the transverse dunes in Tarnata is predominantly accumulative. This pattern can be explained by their geographical position, enclosed between three surrounding reliefs in the Tarnata area, and by their location at the terminal zone of the aeolian flow. Such findings reveal the presence of significant sand dynamics in the region, which vary locally depending on multiple environmental factors. This variability is likely to influence the overall functioning of the surrounding oasis ecosystem. From a management perspective, these results highlight the importance of implementing measures aimed at reducing sediment mobility and limiting dune encroachment. In particular, the stabilization of sediment source areas through the preservation and enhancement of vegetation cover represents an effective strategy for reducing sediment entrainment and aeolian transport. Furthermore, maintaining the geomorphological integrity of the Draa Wadi system is essential for preserving natural sediment-transfer processes. Activities that promote channel incision, excessive sediment extraction, or morphological disturbance should therefore be carefully managed, as they may increase sediment availability and consequently enhance the supply of sandy material feeding the active dune system.

6. Conclusion

The study conducted on the transverse dunes of the Ternata oasis has revealed the complexity of morpho-sedimentary dynamics within a semi-enclosed Saharan context, which is strongly influenced by the seasonal variability of the wind regime and by local topogeographical factors. By employing an integrated methodological approach combining high-precision topographic surveys, spatial analyses, and cartographic representations it was possible to rigorously characterize the morphological evolution, mobility, and the processes of erosion and accumulation affecting the studied dunes. Consequently, this allowed for a deeper understanding of the aeolian functioning and dynamics within the region.

The results obtained highlight, on the one hand, a general tendency toward accumulation, reflecting the sustained activity of wind-driven sediment transport in the area; and, on the other hand, distinct seasonal behaviors among the dunes, indicative of their sensitivity to variations in wind regimes and their specific geomorphological positioning. This spatial and temporal heterogeneity underscores the importance of a fine-grained and context-specific interpretation of aeolian dynamics at the local scale.

From a broader perspective, these dune dynamics through their direct impact on soil resources and the stability of peripheral oasis environments emphasize the need to establish regular monitoring systems and implement appropriate land management strategies, in order to preserve the ecological balance of these fragile environments in the face of increasing climate change effects.

Data availability statement

The current manuscript has no data associated that has been deposited into a publicly available repository. Data may be made available on reasonable request.

Articulo Aceptado / Paper Accepted

References

Adesina, E., Ajayi, O., Odumosu, J., Illah, A. (2024). Assessing the risk of soil loss using geographical information system (GIS) and the revised universal soil loss equation (RUSLE). *Advanced GIS*, 4(2), 42–53.

Ait Hamza, M., El Faskaoui, B., Fermin, A. (2010). Les oasis du Drâa au Maroc : rupture des équilibres environnementaux et stratégies migratoires. *Hommes & Migrations*, 1284, 56–69. https://doi.org/10.4000/hommesmigrations.1241

Anthony, E.J., Besset, M., Zainescu, F., Sabatier, F. (2021). Multi-decadal deltaic land-surface changes: Gauging the vulnerability of a selection of Mediterranean and Black Sea river deltas. *Journal of Marine Science and Engineering*, 9, 512. https://doi.org/10.3390/jmse9050512

Atiki, N., Tnourji, H., Nmiss, M., Ouammou, A. (2021). *Dynamique des vents et leurs implications dans la répartition des dunes dans la plaine de Souss Massa (Centre-Ouest du Maroc)*. Publications de la Faculté des Lettres et des Sciences Humaines d'Oujda, 103–109.

Aydda, A., Althuwaynee, O.F., Pokharel, B. (2020). An easy method for barchan dunes automatic extraction from multispectral satellite data. *IOP Conference Series: Earth and Environmental Science,* 419, 012015. https://doi.org/10.1088/1755-1315/419/1/012015

Bagnold, R.A. (1941). *The physics of blown sand and desert dunes*. New York, NY: William Morrow.

Benbih, M. (2025). *Morphodynamique éolienne dans le Moyen Drâa : du diagnostic au suivi et à la quantification*. Thèse de doctorat, Université Ibn Zohr, 272 p.

Benbih, M., Laaouane, M., Ouammou, A. (2023). État du lieu environnemental et évolution de l'habitat dans les zones arides oasiennes : cas de Fezouata, Moyen Drâa (Maroc). *Revue de Géomaghreb*, 18, 32–42.

Benbih, M., Laaouane, M., Ouammou, A., Akonad, H., Nmiss, M. (2022). *Dynamique des systèmes dunaires et devenir des unités de phœniciculture de Fezouata, Moyenne Drâa, Maroc*. Publications de la Faculté des Lettres et des Sciences Humaines Mohamed Ier d'Oujda, 147–152.

Benbih, M., Ouammou, A., Nmiss, M., Boukdoun, A., Nait-si, H. (2025a). Impacts anthropiques sur la dégradation des sols et la durabilité des écosystèmes oasiens du Moyen Drâa (Maroc). *Revista de Estudios Andaluces,* (50), 266–285. https://doi.org/10.12795/rea.2025.i50.12

Benbih, M., Ouammou, A., Nait-si, H., Nmiss, M. (2025b). Remote sensing based monitoring of dune mobility using the enhanced normalized difference sand index in the Middle Draa, Morocco. *International Journal of Engineering and Geosciences,* 11(1), 106-119. https://doi.org/10.26833/ijeg.1654554

Benbih, M., Ouammou, A., Nmiss, M., Nait-si, H., Boukdoun, A. (2025c). Apport des systèmes d'information géographique (SIG) au suivi de la géodynamique des barkhanes dans le Moyen Drâa, Maroc. G*éomatique et Gestion des Territoires*, 2(1), 174–184. https://doi.org/10.34874/PRSM.GGT-2025.V2.N1.3867

Benbih, M., Nmiss, M., Ouammou, A., Nait-si, H., Ben Kacem, A. (2026). Multi-temporal quantification of sand flux using BSNE and Leatherman traps in the Middle Drâa watershed, Morocco. *Turkish Journal of Engineering*, 10(2), 314-327. https://doi.org/10.31127/tuje.1729820

Bentaleb, A. (2008). *La dynamique de désertification dans le bassin du Drâa moyen : analyse et perspectives*. Thèse de doctorat, Université Mohammed V-Agdal, 285 p.

Beraaouz, M., Macadam, J., Bouchaou, L., Ikenne, M., Ernst, R., Tagma, T., Masrour, M. (2019). An inventory of geoheritage sites in the Drâa Valley (Morocco): A contribution to promotion of geotourism and sustainable development. *Geoheritage*, 11, 241–255. https://doi.org/10.1007/s12371-017-0256-x

Bijaber, N., Rochdi, A., Yessef, M., El Yacoubi, H. (2024). Mapping the structural vulnerability to drought in Morocco. *International Journal of Engineering and Geosciences,* 9(2), 264–280. https://doi.org/10.26833/ijeg.1404507

Bristow, C.S., Bailey, S.D., Lancaster, N. (2000). The sedimentary structure of linear sand dunes. *Nature*, 406(6791), 56–59. https://doi.org/10.1038/35017535

Cailleux, A., Tricart, J. (1959). *Initiation à l'étude des sables et des galets* (Vol. 5). Paris : CDU.

Callot, Y., Crépy, M. (2018). Le rôle de l'alimentation en sable dans la dynamique des dunes linéaires : un changement de paradigme ? *Géomorphologie : relief, processus, environnement*, 24(3), 225–235. https://doi.org/10.4000/geomorphologie.12365

Articulo Aceptado / Paper Accepted

Elbelrhiti, H. (2011). Suivi morphodynamique des barkhanes par couplage télédétection et mesures GPS : application au sud-ouest du Maroc. *Télédétection*, 10, 32–42.

El-Bouhali, A., Amyay, M., El Ouazani Ech-Chahdi, K. (2024). Changes in water surface area of the Middle Atlas–Morocco lakes: A response to climate and human effects. I*nternational Journal of Engineering and Geosciences*, 9(2), 221–232. https://doi.org/10.26833/ijeg.1391957

FAO. (1986). *National action plan to combat desertification – Morocco*. Rome : Organisation des Nations Unies pour l'Alimentation et l'Agriculture.

FAO. (2016). *Date palm cultivation and protection of oasis ecosystems*. Rome: Organisation des Nations Unies pour l'Alimentation et l'Agriculture.

Fryberger, S.G. (1979). Dune forms and wind regime. In E. D. McKee (Ed.), *A study of global sand seas* (pp. 137–169). U.S. Geological Survey Professional Paper 1052.

Goudie, A.S., Livingstone, I., Stokes, S. (1999). *Aeolian environments, sediments and landforms*. Wiley.

Karmaoui, A., Messouli, M., Yacoubi Khebiza, M., Ifaadassan, I. (2014). Environmental vulnerability to climate change and anthropogenic impacts in drylands: pilot study, Middle Drâa Valley, South Morocco. *Journal of Earth Science & Climatic Change*, S11, 2. https://doi.org/10.4172/2157-7617.S11-002

Kocurek, G., Ewing, R.C. (2005). Aeolian dune field self-organization: Implications for the formation of simple versus complex dune-field patterns. *Geomorphology,* 72(1–4), 94–105. https://doi.org/10.1016/j.geomorph.2005.05.005

Lancaster, N. (1995). *Geomorphology of desert dunes*. Routledge.

Livingstone, I., Warren, A. (1996). *Aeolian geomorphology: An introduction*. Longman.

McEwan, I.K. (1993). Bagnold's kink: A physical feature of a wind velocity profile modified by blown sand. *Earth Surface Processes and Landforms*, 18(2), 145–156.

McKee, E.D. (1979). Introduction to a study of global sand seas. In E. D. McKee (Ed.), *A study of global sand seas* (pp. 1–19). U.S. Geological Survey Professional Paper 1052.

McKenna Neuman, C., Nickling, W.G. (1994). Momentum extraction with saltation: Implications for experimental evaluation of wind profile parameters. *Boundary-Layer Meteorology*, 68(1–2), 35–50. https://doi.org/10.1007/BF00712663

Moumane, A., Al Karkouri, J., El Ghazali, F., Benmansour, A., Fico, J., Karmaoui, A., Batchi, M. (2022). Monitoring long-term land use, land cover change, and desertification in the Ternata oasis, Middle Drâa Valley, Morocco. *Remote Sensing Applications: Society and Environment*, 26, 100745. https://doi.org/10.1016/j.rsase.2022.100745

Nmiss, M., Amyay, M., Atiki, N., Benbih, M., Nait-si, H. (2025a). Quantifying sediment flux under moderate wave energy on beaches south of Agadir, Morocco. *Ecological Engineering and Environmental Technology*, 26(1), 78–91. https://doi.org/10.12912/27197050/195526

Nmiss, M., Amyay, M., Atiki, N., Ouammou, A., Benbih, M., Nait-si, H. (2025b). Seasonal morphological changes and grain size distribution mapping on the Massa beaches using topographic survey and GIS. I*nternational Journal of Engineering and Geosciences*, 10(2), 272–289. https://doi.org/10.26833/ijeg.1598677

Rahman, M. (2025). GIS-based allowable bearing capacity thematic maps of shallow foundation for Bogura District, Bangladesh. *International Journal of Engineering and Geosciences*, 10(3), 329–338. https://doi.org/10.26833/ijeg.1589939

Tsoar, H. (1984). The formation of seif dunes from barchans: A discussion. *Zeitschrift für Geomorphologie,* Supplementary Issues, 28(1), 99–103.

Tsoar, H. (2001). Types of aeolian sand dunes and their formation. In N. J. Balmforth & A. Provenzale (Eds.), *Geomorphological Fluid Mechanics* (pp. 403–429). Springer. https://doi.org/10.1007/3-540-45670-8_17

Ungar, J.E., Haff, P.K. (1987). Steady state saltation in air. *Sedimentology*, 34(2), 289–299. https://doi.org/10.1111/j.1365-3091.1987.tb00778.x

Wiggs, G.F.S. (2001). Desert dune processes and dynamics. *Progress in Physical Geography,* 25(1), 53–79. https://doi.org/10.1177/030913330102500103

Articulo Aceptado / Paper Accepted