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Geomorphic changes in sand dunes over the last two decades in Al-Huwaimiliyah belt, northwestern Kuwait

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Abstract

Objectives: Sand dunes in Al-Huwaimiliyah belt have been experiencing drastic changes in both dune distribution and formation rate. The goal of this study is to identify the rate change of sand dunes in the southern Al-Huwaimiliyah belt over the course of nineteen years. **Method:** The study relied on using geographic information system and regression analysis to perform differencing analysis and predictions of dune movement in Al-Huwaimiliyah dune field. **Results:** The surface geomorphological features of Kuwait are directly affected by ongoing erosion processes. Al-Huwaimiliyah dune belt of 1,762,577 square meters showed an interesting pattern of dune change in number, size, and dimension between 2005 and 2024. It was found that sand dunes have been moving further southeast toward the urban area, changing in dimensions by an overall loss and gain of -3.26 and 3.93 meters over the course of nineteen years. Our prediction model, despite overestimation of dune dimension, shows an agreement in the pattern of dune geomorphic changes over time. **Conclusion:** The observed mobility and sand dunes migration toward the urban area indicate that wind activities can change geomorphic characteristics of sand dunes overtime. These changes threaten the urban area of Kuwait due to the dunes adjacent location to major facilities and roads, which are considered a threat on both natural and urban environments and require intensifying protection methods to prevent dune encroachment. The results of this study may serve decision makers in implementing strategies to defeat sand dunes encroachment onto roads and urban areas.

Keywords: sand dunes, remote sensing, GIS, desert geomorphology, aeolian depositional features, the evolution of natural phenomena

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التغيرات الجيومورفولوجية للكثبان الرملية في حقل الهويميلية شمال غرب دولة الكويت خلال عقدين من الزمن

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ملخص

الأهداف: تسلط هذه الدراسة الضوء على تأثير العمليات الريحية؛ مثل التعرية والترسب على الكثبان الرملية في حزام الهويميلية الذي شهد تغيرات جذرية في كل من توزيع الكثبان الرملية وحركتها ومعدل تكوينها. **المنهج**: استخدام نظم المعلومات الجغرافية لتعرّف معدل تغير الكثبان الرملية في حزام الهويميلية الجنوبي، الذي تبلغ مساحته 1,762,577 متراً مربعاً فيما بين عامي 2005 و2024، ودراسة آثار التغيرات الجيومورفولوجية على كل من المناطق الطبيعية والحضرية في دولة الكويت، عن طريق المتابعة الزمنية لحركة الكثبان الرملية بالأقمار الاصطناعية واستخدام المنهجية الإحصائية لتنبؤ حركتها في المستقبل. **النتائج:** تبين الدراسة أن عدد الكثبان الرملية تغير في حقل الكثبان الرملية الجنوبي؛ إذ تحركت الكثبان باتجاه الجنوب الشرقي نحو المنطقة الحضرية، وتغيرت في أبعادها خلال هذه الفترة الزمنية؛ فقد فقدت واكتسبت ما بين -3.26 و3.93 أمتار من ارتفاع رمالها على مدار تسعة عشر عاماً. **الخاتمة:** تهدد هذه التغيرات الجيموروفولوجية المنطقة الحضرية في دولة الكويت؛ بسبب قرب الكثبان الرملية من المرافق والطرق الرئيسية، وتشكل التغيرات الجيومورفولوجية في الكثبان الرملية تهديداً لكل من المناطق الطبيعية والحضرية، وتتطلب أساليب حماية مكثفة لمنع زحف رمالها نحو المناطق المأهولة لتجنب الكوارث الطبيعية والخسائر الاقتصادية. قد تفيد نتائج الدراسة صناع القرار بإيجاد أفضل الطرق والحلول للحد من زحف رمال الكثبان الرملية نحو المنطقة الحضرية.

الكلمات المفتاحية: الكثبان الرملية، الاستشعار عن بعد، نظم المعلومات الجغرافية، جيمورفولوجيا الصحارى، الظواهر الإرسابية الريحية، تطور الظواهر الطبيعية

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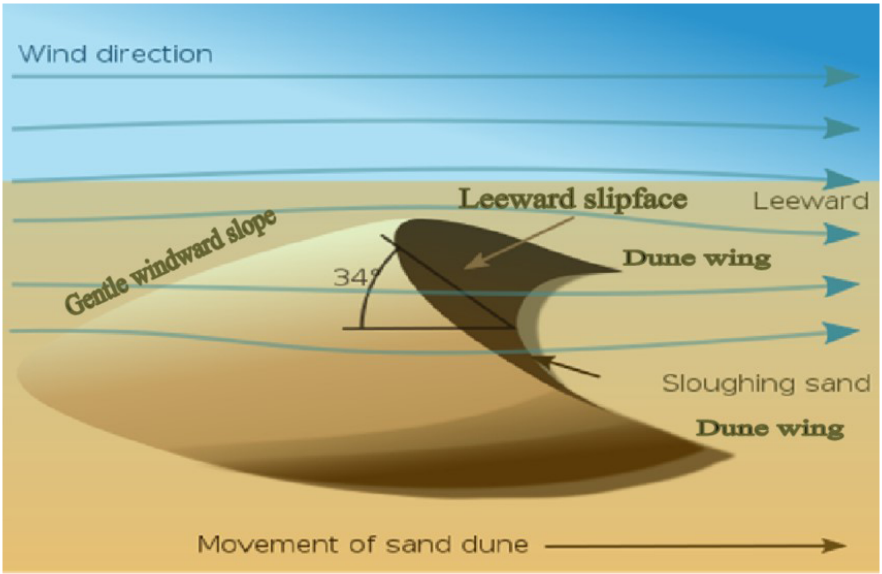
Introduction

Owing to the location of Kuwait between two regions with different natural characteristics, that is, the Arabian Peninsula in the southern and southwestern regions and flood plains in the northern and northeastern regions, its surficial forms have clearly been affected. The surface geomorphology has mainly been affected by exogenic processes (occurring on the surface) which can be attributed to wind depositional activities. Sand dunes are the most prominent depositional features in the Kuwaiti desert; they can be clearly observed in satellite images in both the coastal and desert environments. Al-Sulaimi and El-Rabaa (1994) conducted a detailed morpho-structural study in which they analyzed and interpreted the geomorphological features in the Kuwaiti desert.

Mobile sand dunes such as barchan dunes are controlled predominantly by northwestern-directed wind and can be found throughout the desert of Kuwait. The concept of dune mobility is complex and can be affected by many natural and human factors such as the expansion of urban areas and human activities, growth of vegetated covers, and shifting wind activities (Alexander, 2007; Thomas et al., 2005). Dune activities and mobility rate are, therefore, affected by the rate change of the surrounding surfaces (Yizhaq et al., 2009). Anthropogenic factors are another complex aspect of dune mobility and migration (Al-Hurban, 2014). Overgrazing and precipitation rate change could also increase dune activities; to illustrate, reduction and instability of the vegetation cover caused by extreme animal activities account for the decrease of evaporation and evapotranspiration and therefore alter precipitation rate. This eventually leads to drought, which disrupts the dynamics and morphologic characteristics of dunes (Fonstad, 2006; Yizhaq et al., 2009). In Kuwait, a variety of instable natural conditions can effectively influence dune mobility, in addition to the persisting human pressure seen in the form of off-road driving, mining, and shifting more infrastructure towards the desert (Khalaf & Al-Ajmi, 1993). For example, the Gulf War disrupted Kuwait's desert pavement (El-Baz & Al-Ajmi, 1993; El-Baz et al., 1994), and the drainage of southern Iraqi marshes played a significant role in increasing the amount of transported aeolian sediments (Munro & Tourron, 1997). This resulted in the acceleration and enlargement of old sand dunes, as well as the formation of new sand dunes (Figures 1 and 2).

Figure 1

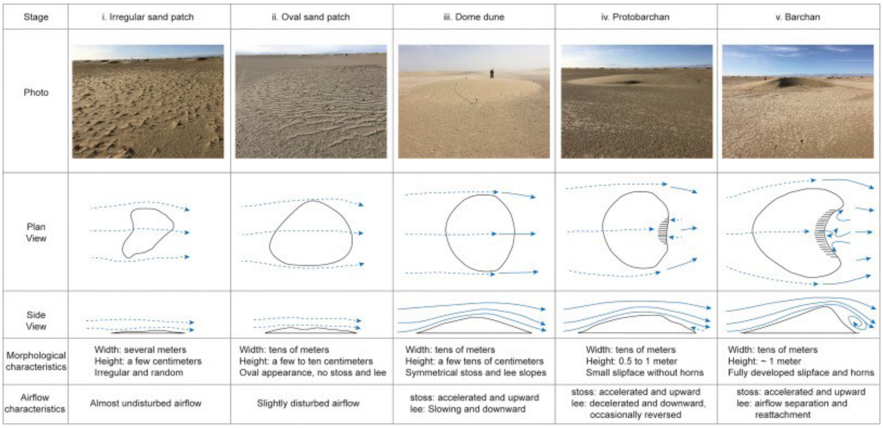
Morphology of Sand Dunes



Source. (Kumar & Abdullah, 2011).

Figure 2

Morphological Cycle of Sand Dunes



Source. (Open Geology, 2024).

This study focuses on the drifted dunes from Al-Huwaimiliyah belt (the southern corridor) in the Jal Al-Liyah area in the north–northwestern part of Kuwait, which are oriented in a northwestern to southeastern direction (Foda & Al-Attiyah, 1982; Khalaf et al., 1984). Through the activation of mobile sand dunes via the dominant northwestern wind direction, dust storms and sandstorms are formed, transporting sand sediments from southern Iraq to the north–northwestern parts of Kuwait (Al-Dabi et al., 1997; El-Baz, 1994; Khalaf & Al-Ajmi, 1993; Khalaf et al., 1995).

The increased rate of aeolian transport of fine particles usually occurs during summer when wind speed reaches 5.4 meters per second, recording 20 m^3 $(m\ width)^{-1}$ yr^{-1}. This eventually contributes to feeding or forming new dunes of various shapes and sizes with an average movement of 20 meters in 9 months (Khalaf & Al-Ajmi, 1993). This accounts for sand dune evolution in Kuwait desert, where encroaching sand dunes have been observed throughout the desert affecting natural reserves and vegetated areas. The rates and quantity of which dunes are moving in the northwestern part of Al-Huwaimiliyah belt in Kuwait desert have been studied for different time-periods, while those of the southeastern part, which is the focus of this study, have been understudied. Mobile dunes have been mapped and quantified in the northern part of the Huwaimiliyah dune field using GIS techniques. The northwestern part of Al-Huwaimiliyah includes more than 2300 dunes, which were mapped in previous studies using remote sensing techniques (Al-Dousari et al., 2022). The study conducted by Al-Dousari et al. (2022) indicated that the dunes move with high variation (between 2 m–24 m per year) depending on their location and size. Studies found that surface roughness may affect dune formation when the conditions are suitable for aeolian processes to take place; to illustrate, Al-Huwaimiliyah outer dunes in the northern part of the field often experience modification to their shape and size due to the nature of the smooth terrain of the field (Al-Dousari & Pye, 2005). These studies focused on the dunes that are located in the vast desert of Kuwait, while this study is focusing on the dunes that are located in the southeastern part of the Huwaimiliyah field. It is important to investigate the southeastern part due to its location that is adjacent to urban activities.

What is worth mentioning is the encroachment of sand dunes into facilities and roads and other urban features that is pronounced as environmental and economic hazard (Khalaf & Al-Ajmi, 1993). The frequent activation of sand dunes allows these dunes to migrate, causing one of the main and crucial environmental problems in Kuwait, which is encroachment of sand on roads, industrial plants, military bases, farmlands, oil plants, and urban utilities in the Kuwait desert. Decision makers in the country face critical environmental challenges and need integrated strategies and sustainable mitigation measures.

The goal of this study is to assess the sand dune corridor of the southern Al-Huwaimiliyah belt in northwestern Kuwait City by investigating the geomorphic changes of the sand dunes in the study area. Dune migration routes and rates from 2005–2024 were monitored in order to understand dune migration dynamics close to the urban area. Satellite imagery, geographic information systems, and remote sensing techniques are utilized to determine the potential future movement of the dunes to propose appropriate solutions and measures to decelerate their movement and migration and keep them away from plants and utilities.

Methods and Materials

Study Site

The state of Kuwait is located at the northwestern corner of the Arabian Gulf and covers an area of 18718 km^2; it is bordered by Iraq to the north and northwest, Saudi Arabia to the south and southwest, and the Arabian Gulf to the east, where 50% of Kuwait's surface area is covered by aeolian deposits (Khalaf, 1989). Kuwait lies between latitudes 28°.30′ and 30°.06′ north and longitudes 46°.30′ and 49°.00′ east. This location has caused Kuwait to be situated downwind of the deflationary area of the Mesopotamian flood plain in southern Iraq.

Kuwait is geographically located in a desert zone. This zone is characterized by a highly variable hyperarid desert continental climate with recurrent extremes, long summers, and short winters. During summer, temperatures are usually high, and the weather is dry. During winter, temperatures become warm, and rain occasionally falls. The climate is marked by four distinct seasons, long, hot, and dry summers and short winters. The maximum daily temperature can reach 45°C during summer, during which no rainfall occurs.

The temperatures range between 45°C in the summer and 6°C in the winter. This great difference in temperature is accompanied by many differences in the annual rates of rainfall, ranging between 22 mm and 352 mm. The highest temperature registered in Kuwait was 51°C in July 1978, whereas the lowest temperature was -4°C in January 1964. The predominant wind direction is northwesterly, and the wind is known as Shamal, which has not changed direction since the installation of the meteorological stations in Kuwait in 1972 (Al-Kulaib, 1990). This wind direction is the major factor contributing to the frequent occurrence of dust and sandstorms in Kuwait because the wind provides airborne dust materials and fine sand particles. The northwesterly winds can reach maximum speeds of 6–7 ms^{-1}. The coastal area experienced an average annual mean sediment fallout of 2300 tons km^{-2} from 1979–1980 (Khalaf & Al-Hashash, 1994). The other occasional wind direction is northeastern, and this wind is free of dust and fine sand particles (Al-Dabi et al., 1997).

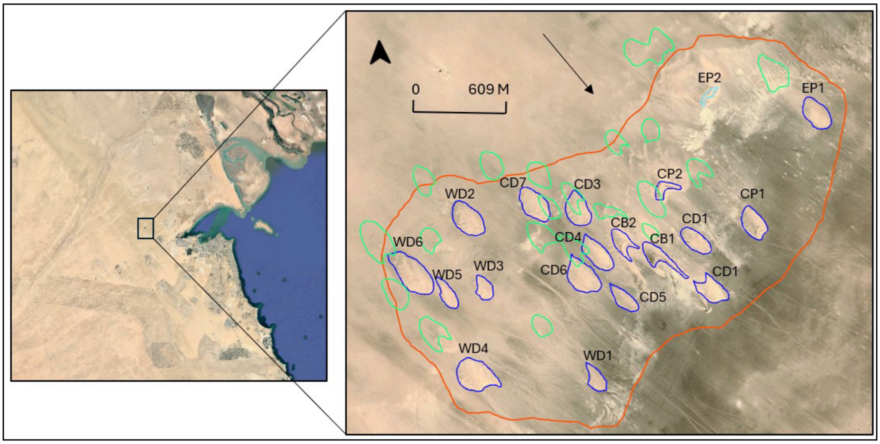
The average annual rainfall is typically approximately 112 millimeters (mm) per year and varies from 75 to 150 mm/yr. The volume of rainfall in Kuwait has been increasingly fluctuating, with wide variability in annual rainfall; the month with the most rainfall is January, with an average rainfall of 0.5 inches, and the month with the least rainfall is June, with an average rainfall of 0.0 inches. In the 1970s, the average annual precipitation was 136 mm, or approximately 30% above the annual mean, whereas in the 1980s, it was 89 mm, or 15% above the annual mean. The monthly mean values of potential evapotranspiration range from 67 mm in January to 324 mm in July. According to the Environmental Public Authority (EPA) records (2019), the average annual rainfall recorded from 1998–2016 was approximately 112 mmy^{-1}, whereas the annual levels recorded by Kuwait Civil Aviation during the same period ranged from 34.4 mmy^{-1} to 218 mmy^{-1} at Kuwait International Airport and 319.5 mmy^{-1} at Umm Almaradim Island in October 2013.

Kuwait is characterized by low to moderate relief, where the main tectonically controlled topographic features are the Wadi Al-Batin area to the northwest rising 325 m above sea level (ASL) and the Jal Az-Zor escarpment of 145 m ASL north of Kuwait Bay (Al-Hurban & Hassan, 2024; Al-Hurban & Hersi, 2008; Al-Sarawi, 1980, 1988). The surface topography is characterized by rather monotonously flat to gently rolling desert plains occasionally dissected into low hills, scarps, and wadis. In the Wadi Al-Batin area, the Wadi Al-Batin valley is the natural border between Kuwait and Iraq to the north and southwest, where some small and isolated hills are located in the south (Al-Hurban & Hassan, 2024). The landscape of Kuwait is gently sloping from approximately 280 m ASL in the extreme southwestern corner of the state toward the Arabian Gulf coast to the east (Khalaf & Al-Ajmi, 1993).

This study was conducted in Al-Huwaimiliyah sand dune corridor, which is located in the southern Huwaimiliyah field in the northwestern part of Kuwait, between latitudes 29°30′ N and 30° N and longitudes 47°30′ E and 47°E. One of the major sand dune fields in Kuwait is Al-Huwaimiliyah sand dune field, which is located in the study area and stretches from the northwestern part to the southeastern part of Kuwait (Figure 3), covering an area of almost 220 km^2. Other geomorphic features, including sand sheets, desert pavement, and playa lakes, exist in the study area. The sand dunes in the area consist mainly of quartz, feldspars, volcanic rock fragments, carbonate, and gypsum, with a minimum grain size of 0.22 mm, a maximum grain size of 0.27 mm, lengths ranging from 150 to 200 m, heights ranging from 3 to 4 m, and widths ranging from 25 to 35 m (Al-Dabi et al., 1997). Sand dunes in this area are known to be mobile, their existence is affected by aeolian activities, and their number may vary throughout the years (Figure 4). The sand dunes were given identifier code including location (E; east, W; west, & C; central), type (B; Barchan, P; parabolic, & D; domal), and number (Figure 3).

Figure 3

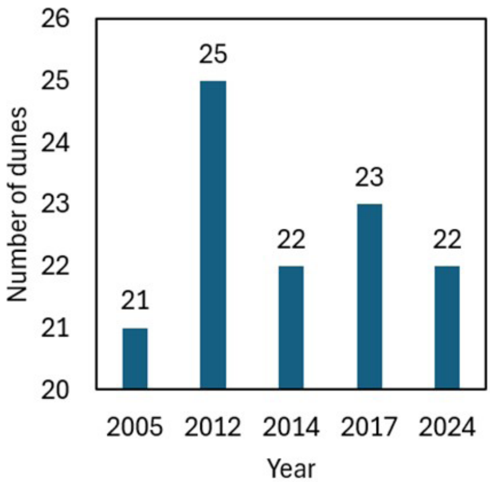
Dune Field in Al-Huwaimiliyah Corridor



Note. The locations of dunes found in 2024 (blue) and their past locations in 2005 (green). One dune, shown in light blue, was excluded from the analysis. The arrow indicates the travel direction of dunes.

Figure 4

Number of Dunes Found in Al-Huwaimiliyah Corridor Dune Field throughout the Study Period



Objectives

The aim of this study is to investigate the geomorphology of southern Al-Huwaimiliyah sand dune belt (corridor) via GIS and remote sensing techniques to monitor their movement and temporal changes during 2005–2024, calculate the annual rate of their movement, and recommend mitigating measures to limit the movement of the dunes. The specific objectives of the study include the following:

- GIS is utilized to investigate the distribution of sand dunes in the study area and study their spread.
- Satellite images covering the period of 19 years (2005–2024) are used to investigate dune migration.

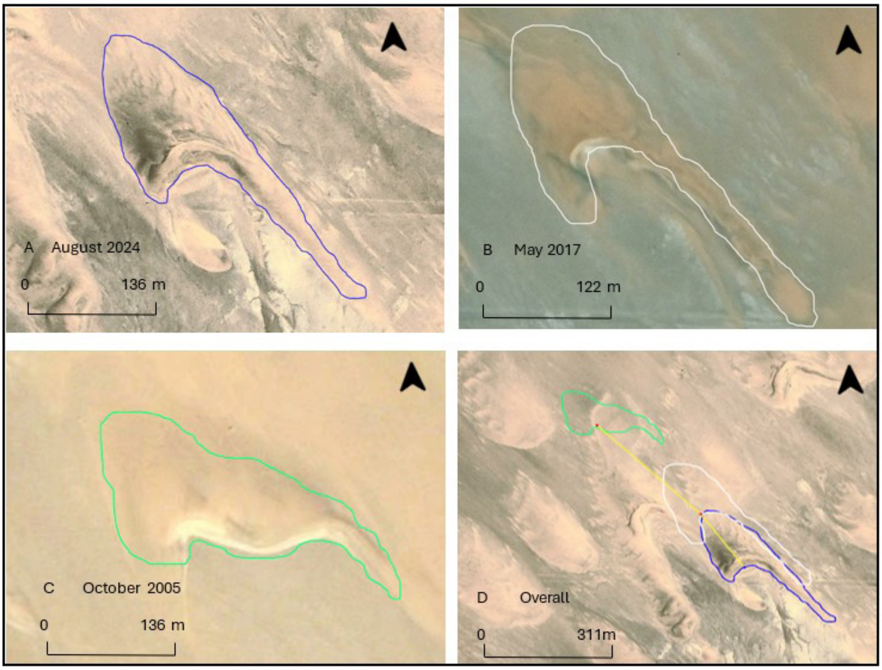
- GIS and satellite images are used to compare the locations of the sand dunes during the study period with the current locations of the dunes.
- An integrated strategy of sustainable measures is proposed for decision makers to address the spread of sand dunes and their environmental impacts on urban and public utilities and installations.
- The locations where sand dunes will arrive in the coming years are found to develop appropriate solutions to stop their movement and keep them away from land use areas.

The study area represents a large part of Al-Huwaimiliyah dune field (Figure 3). Nineteen dunes were included in the analysis, while one dune was excluded due to uncertainty in monitoring its past morphology (Figure 3, light blue). The cumulative change in the dune field was monitored for the period between 2005 and 2024 via Google Earth Pro, Landsat 8 imagery (resolution of 30 m), and analyzed in ArcMap 10.8.2.

The dunes were identified individually in Google Earth Pro. A polygon was drawn for each dune, covering their full extents, for different periods for comparison (2005, 2017, 2024; Figures 5-7). Multiple transect lines were manually overlaid on the dunes to compute and extract the dune size, area, and elevation.

Figure 5

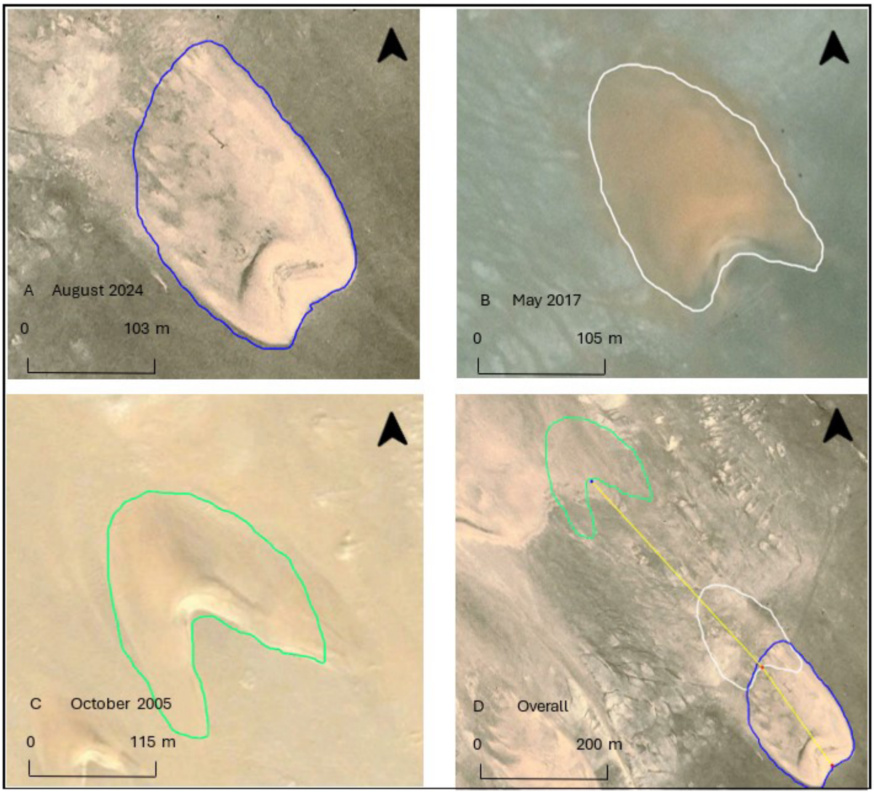
Barchan Dune Evolution During 2005, 2017, and 2024



Note. The arrow indicates dunes travel direction.

Figure 6

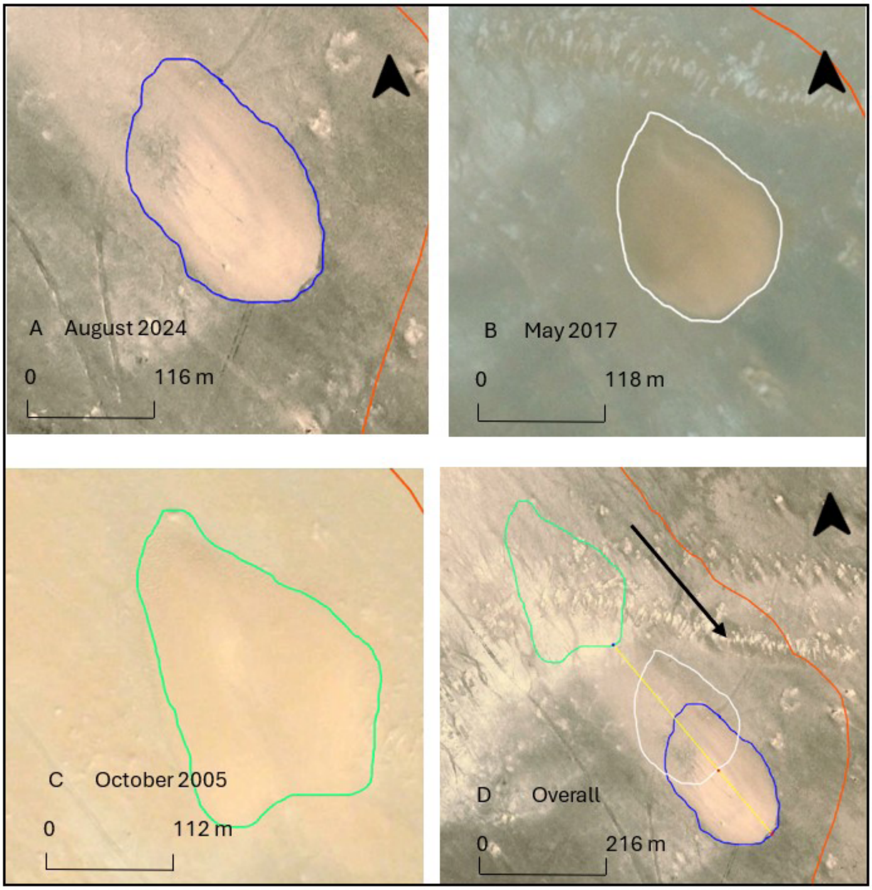
Parabolic Dune Evolution During 2005, 2017, and 2024



Note. The arrow indicates dune travel direction.

Figure 7

Domal Dune Evolution During 2005, 2017, and 2024



Note. The arrow indicates dune travel direction.

To better understand the mechanism of dune travel in Al-Huwaimiliyah dune field, three different dunes representing primary dune morphologies in Kuwait's desert were selected for computing the travel distance. The selected dune types, that is, parabolic, barchan, and domal, were studied for three different periods: 2005, 2017, and 2024 (almost 2 decades). In addition to computing the dune dimensions, Landsat imagery was used to compute gain/deposition and loss/erosion (meters) in the accumulation of dune sand along the extent of the dune for each year (Table 1).

Table 1

Dune Parameters (meters), Area (square meters), Loss and Gain of Sand Accumulation along the Dune (meters), and Travel Distance (meters)

Year	Parabolic			Domal			Barchan		
	October 2005	May 2017	August 2024	October 2005	May 2017	August 2024	October 2005	May 2017	August 2024
Parameter (m)	399	328	380	440	360	399	364	654	550
Area (m^2)	6435	6252	9307	11497	9129	10146	4619	8832	7756
Gain/Loss (m)	0.06 – -2.38	0 – -1	0.23 – -1.82	0.66 – -1.45	0.23 – -2.05	1.93 – -0.58	1.53 – -1.2	0.70 – -1.44	0.25 – -2.25
Travel distance 2005–2017	242.92			159.69			182.17		
Travel distance 2017–2024	118.27			76.31			95.79		
Overall travel distance	357.84			235.77			281		

Change in Elevation of the Dune Surface

The ArcMap Rater Calculator was used to detect and quantify the morphological changes in the quantity of the dune sand and location of the dune over time. Temporal changes in the dune field were detected by comparing two different elevation rasters from different periods. First, elevation profiles were extracted from Landsat 8 images for the desired years and then imported into ArcMap 10.8.2 to create elevation maps. Differencing analysis (James, et al., 2012) was then performed to produce maps of the elevation changes between 2005 and 2024 (Figure 8D) via a simple algebraic procedure in ArcMap (Equation 1). The difference represents the cumulative change in the dune surface elevation (DSEC) over 19 years:

$$DSEC_{19\ YEARS} = DEM_{2005} - DEM_{2024} \qquad \text{(Eq. 1)}$$

Classification (supervised) maps were produced to indicate areas of erosion and deposition of sand in the dune field over 19 years. The negative values produced in the maps of the elevation difference were classified as sand losses, and the positive values were classified as sand gains. Losses are attributed to erosion, and gains are attributed to deposition. The map classifications were reduced to two major classes, eliminating surrounding open areas and sand sheets to reduce error in identifying changes in sand dunes alone.

Dune Elevation Profiles

Elevation profiles were extracted from each dune that was detectable in the field between 2005 and 2024. In this process, the baseline was set to 2005, while the 2012, 2016, 2017, and 2023 Landsat images were used to detect the paths of sand dune movements. The extraction was performed by first defining the extent and size of dunes via polygons. Multiple transact lines were then drawn along the extent of the dunes to determine the profiles. The profiles represent the elevation of the dunes and the ground as if the dunes were fixed to the ground. The relationships between the elevation (meters) and distance (meters) represent the X (vertical) and Y (horizontal) dimensions of the dunes (Figure 8).

Predictions of Sand Accumulation and Elevation

A regression model (Hoshmand, 2017) (Equation 2) was developed to predict the elevation of dunes in Al-Huwaimiliyah dune corridor by considering 19 years of sand erosion and deposition between 2005 and 2024. Equation 2 is as follows:

$$DSEC_{Estimated} += c_0 + c_{Elevation} + f_{Elevation} \quad \text{(Eq.2)}$$

Where is a constant, is a coefficient, and is the estimated value of dune elevation in the field. This method was used for predicting sand accumulation for three types of dunes in the field: domal, barchan, and parabolic (Figures 5–7). Then, prediction regression was applied to the entire dune field to produce quantitative and classified maps of site elevation and create a predicted difference map showing areas of sand loss and gain.

The assumption was built on the hypothesis that dunes move at a rate (approximately) of distance/year similar to that between 2005 and 2024 for each dune. For example, the calculation is as follows: travel distance × overall period; if a dune moved a maximum distance of 200 m in 19 years (2005–2024), the travel distances were 0.028 m per day and 10.526 m per year.

The uncertainty of the prediction was computed with the root mean square error (Bishop & McBratney, 2001) (RMSE):

$$RMSE = \left(\sum_{j=1}^{n}\left(DSEC_{Estimated}^{j} - DSEC_{Landsat}^{j}\right)^{2}\right)^{1/2} \quad \text{(Eq.3)}$$

where represents the DSEC estimate for the j^{th} value from either the regression (‘Estimated’) or Landsat 8 extracted estimate (‘Extracted’), respectively, and n is the total number of values under consideration. The value of n varies between dunes depending on the dune dimension.

Results

The selected area of Al-Huwaimiliyah dune corridor covers approximately 5,613 meters (distance) and an area of 1,762,577 square meters, where the wind is highly active and shapes landforms, especially sand dunes. In Al-Huwaimiliyah dune corridor, the number of dunes has changed over time (Figure 4). The lowest number of dunes was found in 2005 and 2024 (21 and 22, respectively), whereas the highest number was 25 dunes in 2012 (Figure 3). This indicates that many dunes have entered and then exited the field over the years and have changed their morphologies along the way due to emergence and erosion. The period between 2005 and 2012 captured the highest rate change in dune count; 19% represents a period of seven years, while the overall (2005–2024) rate change of dune number in the field was 5%. The area was 46% covered by dunes in 2024 (Table 2.)

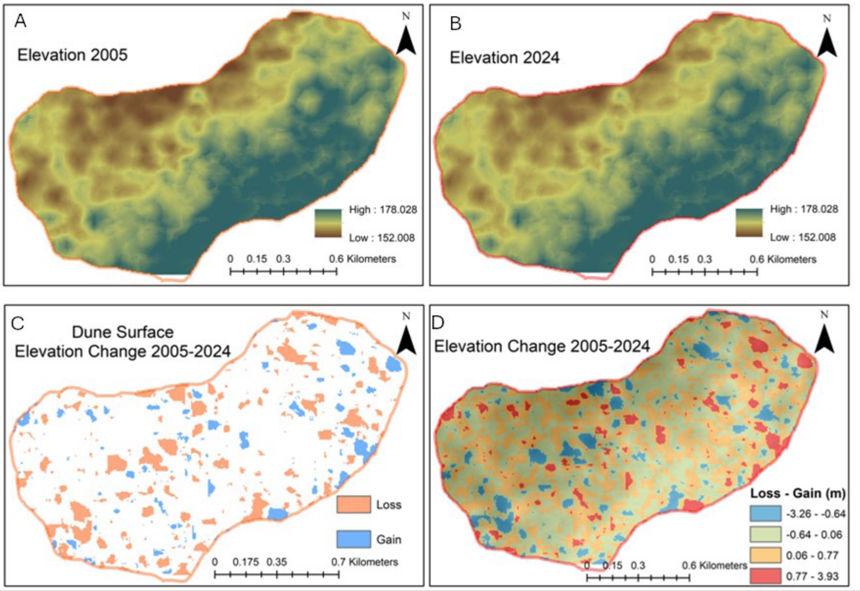
Table 2

Total Number of Dunes for the Years Captured by Satellite Imagery and the Corresponding Percentage of Change between Each Period of Time

Year	Number of dunes	Percent of change	Overall rate change 2005-2024 (%)	Dune area coverage (%)
2005	21		5	46
2012	25	19		
2014	22	-12		
2017	23	5		
2024	22	-4		

Figure 8

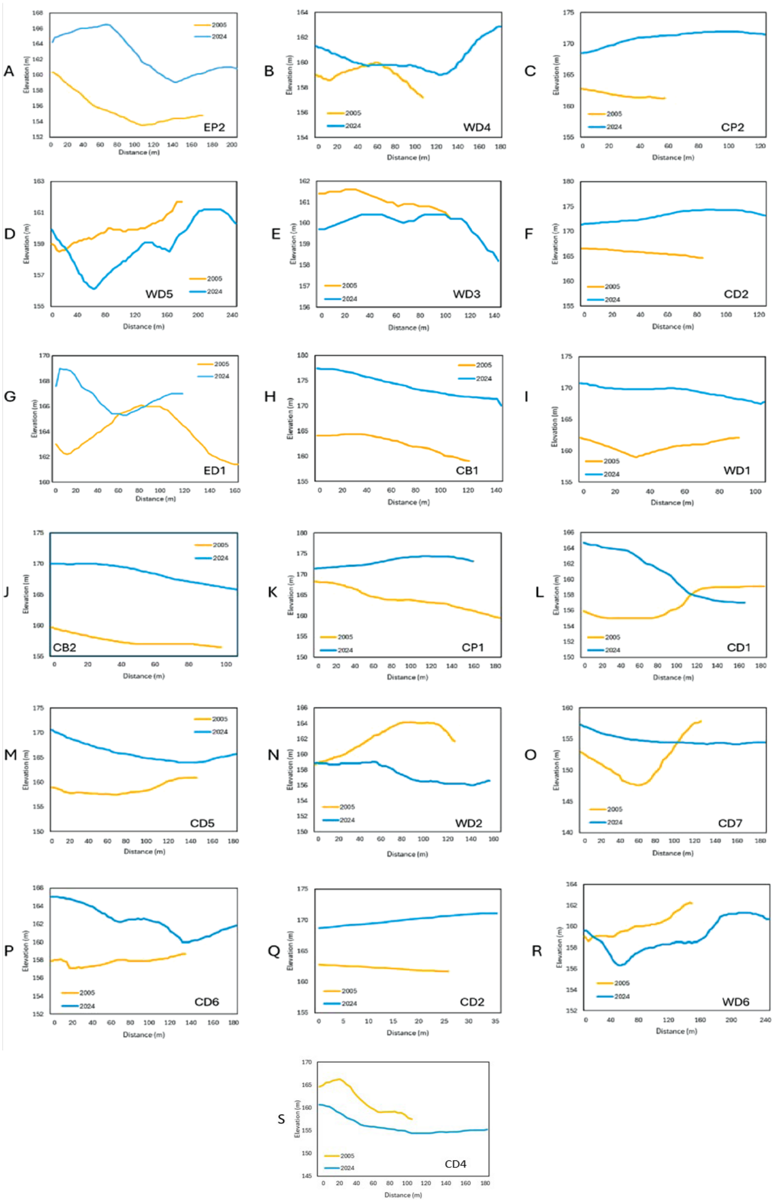
Elevation of Al-Huwaimiliyah Dune Field in 2005 (A) and 2024 (B). (C) Classification of elevation changes due to sand gains and losses. (D) Elevation difference (m) between 2005 and 2024.



The results (Figure 8D) form the map showing the differences, that is, the change in sand accumulation over time, which can be either a positive value reflecting the increase in sand accumulation (deposition) or a negative value reflecting the loss in sand accumulation (erosion). The results indicate an overall loss and gain of -3.26 and 3.93 m of accumulated sand. This result includes the dunes and the surrounding sand sheets in the field, whereas Figure 8C (classification) indicates the sand dunes whose morphologies changed between 2005 and 2024 due to erosion, deposition, and migration.

Figure 9

Comparison of Sand Dune Profiles between 2005 and 2024 for each Dune in Al-Huwaimiliyah Corridor



The profiles of the dunes indicate that the majority of the dunes have increased in the x-dimension, which means that the size of the dunes has increased due to aeolian activities. Deposition is the cause of the increase in the horizontal extent of the dunes because more sand is added to the dunes. Five of nineteen dunes decreased in elevation (Figure 9E, D, N, S, and R); the change in the y-dimension may indicate that erosional processes have taken place around some dunes, resulting in the loss of dune sand in terms of its vertical extent, whereas changes in other directions indicate deposition due to increasing elevation, which indicates the addition of more particles into the accumulated dune sand. Wind can play a role in changing the dune shape and morphology, including destroying the morphometric characteristics of dunes and enlarging or shrinking the size of dunes vertically and horizontally. The majority of the dunes in the southeastern corridor were domal type with an average elevation of 162.9 meters, while only two were parabolic with an average elevation of 169.3 meters (Table. 3)

Table 3

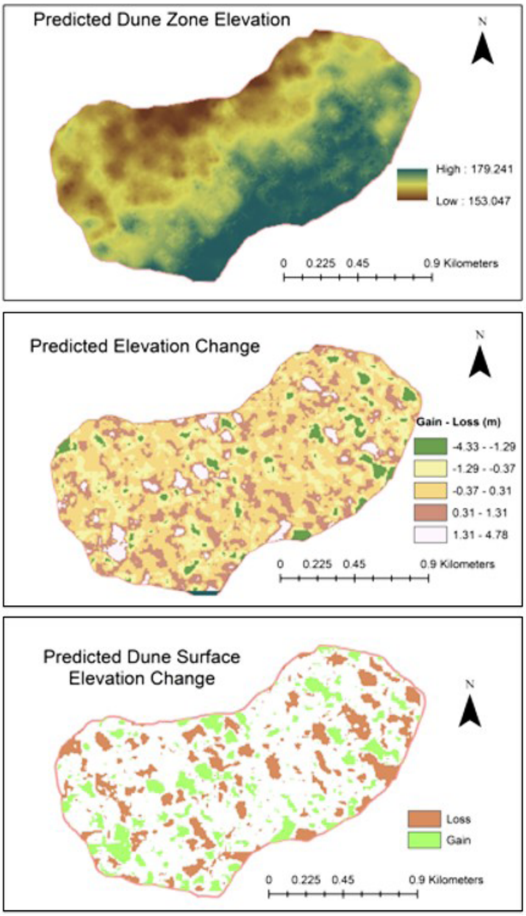
Dune Number (count) of each Dune Type in the Field with Elevation Ranges and Averages in Meters

Dune Type	Count	Dune elevation range (m)	Dune mean elevation (m)
Domal	11	153 – 177.5	162.9
Parabolic	3	168.6 – 172	169.3
Barachan	2	156.8 – 171.2	164.7

The results from the prediction model (Figure 10) show interesting agreement with the results shown on the difference map computed for 2005 to 2024 in terms of areas of soil loss and accumulation due to dune migration; however, the regression overestimated the gains and losses of dune surface elevation. The predicted difference map shows distinctive areas of accumulation and loss between 1.31 and 4.78 m, which are also shown on the estimated difference map (Figure 8). However, overall, the predictions overestimated the magnitude of erosion and deposition.

Figure 10

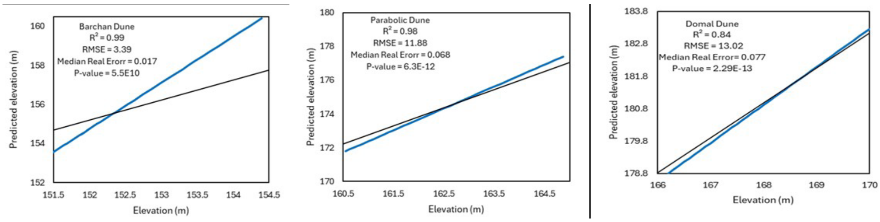
Predicted Elevations in Al-Huwaimiliyah Dune Field and Predicted Elevation Changes in Al-Huwaimiliyah Dune Field



The predictions for the dunes in the field (Figure 11) show a high predicted correlation for the selected parabolic, barchan, and domal dunes. The highest predicted correlation was found for barchan dunes, with $R^2 = 0.99$ and RMSE = 3.39, and the lowest correlation was for domal dunes, with $R^2 = 0.84$ and RMSE = 13.02, whereas parabolic dunes had values of $R^2 = 0.98$ and RMSE = 11.88. However, the model overestimated the individual magnitude of change in these dunes.

Figure 11

Correlations Showing the Relationships between Predicted Dune Elevations and Extracted (real) Dune Elevations for Barchan Dunes (left) and Domal Dunes (right)



Discussion

Aeolian processes are key to the formation and development of geomorphological landscapes in drylands. Compared with other regions, drylands are more susceptible to aeolian processes because of deteriorated vegetation cover, a lack of rainfall, the abundance of bare soil areas, and, more importantly, wind activities (Li et al., 2008; Okin, 2008; Okin et al., 2006; Sufardi, 2024). Kuwait is a zone for active aeolian processes and is known for its dust storms and sand creep (Walia et al., 2024). Many aeolian features in the Kuwait desert are attributed to aeolian activities, such as sand dunes, sand sheets, and ripples (Al-Hurban & Al-Ruwaih, 2023). In vulnerable ecosystems, such as the Kuwait desert, aeolian processes can affect ecosystem stability, where ecological habitats, microenvironments, recreational activities, and urban environments can deteriorate through the destruction and movement of sand dunes. Therefore, aeolian processes are considered among the most dominant and effective processes shaping the desert of Kuwait and its geomorphology (Al-Sulaimi & Mukhopadhyay, 2000; Shahid, 2023).

Al-Huwaimiliyah corridor lacks vegetation cover, which makes it suitable for aeolian activity and sediment transport by wind into and from dunes. These conditions make Al-Huwaimiliyah a field where erosion is actively occurring, affecting both deposition and erosion. Northwesterly winds contribute largely to changing the geomorphic characteristics of Al-Huwaimiliyah field. The damage to and shift of dunes are disastrous for natural and urban environments. The erosion of dunes results in the loss of habitats and biodiversity (Bird et al., 2020). Where there is little vegetation, there is a high probability that the area and its surroundings will become more arable due to dune movement. The stability of the ecosystem and surrounding areas in Kuwait's desert is expected to be enormously affected by dune migration, especially in areas where vegetation cover thrives (Burca, 2024). Our study captured migration of different types of dune morphologies such as barchan, domal, and parabolic. These dunes showed high mobility rate; however, these are slower in movement than northern Al-Huwaimiliyah dunes as reported in previous studies. In our studies, the migration rate ranges between 10 and 20 m per year (approximately 230–370 m per 19 years). This rate varies due to dune size, type, and sand collection, while the dunes in northern Al-Huwaimiliyah field were monitored for the years 1972 and 1992 and recorded an average migration rate of 24 m per year with high variation among dune type and size, where larger dunes moved slower than smaller dunes (Al-Dousari & Pye, 2005).

The erosion and migration of dunes in Kuwait could result from natural factors, such as high-speed winds, and human activities, such as urbanization. This results in negative implications for the environment, such as the loss of habitat, widespread desertification, and economic downturns (Bird et al., 2020). Al-Huwaimiliyah dunes are dynamic in nature and are considered a threat to the surrounding natural and urban environments. Importantly, the dunes are surrounded by numerous local ranches to the east (3,214 m away), local roads (5,600 m away), and primary highways (15,500 m), according to Google Earth observations (November 2024). In urban regions, sand dune migration causes issues, particularly to roads and buildings, by encroaching on them or losing their accumulated sand to wind, causing sand creep around urban environments. Moreover, shifting dunes can close highways and increase repair and maintenance costs, diminishing what people once saw as a solution to their transportation issues (Abdullah et al., 2021). Thus, migrating dunes have substantial economic and logistical impacts on towns and cities. Revegetation, artificial barriers, and rational land management policies could be used as countermeasures (Al-Awadhi & Misak 2000). These findings can help minimize the consequences of dune erosion and preserve the natural and human-made environments in Kuwait simultaneously.

Conclusion

Many dunes in Kuwait desert are frequently eroded through the blowing of strong northwesterly winds that occur specifically during the summer and spring seasons. Kuwait experiences strong winds, making dunes particularly vulnerable to wind erosion. Strong winds blowing soil particles could eventually erode the whole dune system over time. In other words, Kuwait's natural environmental conditions promote wind-induced erosion. Our results indicate that dunes have been moving rapidly toward the urban environment and that their size and dimensions have been increasing due to aeolian inputs and emergence. For example, winds provide some sand dunes with particles that change their morphologies, eventually causing them to drift and change in shape and size. The rapid changes in sand dune morphologies addressed in our study are robust and require more scientific attention. Our prediction model, despite overestimation, highly agrees with dune morphology, migration, and profile data, indicating that the dunes are dynamic and will continue to move in the future, which may place the surrounding natural and urban environments under pressure. Reducing the destructive impacts of dune erosion and migration requires measures implemented as a result of environmental management policies to sustain the stability of urban and natural environments.

Recommendations

Remote sensing is a powerful tool that can be used to study the geomorphology of dunes over time, especially dune migration and encroachment, which are considered threats to urban environments, natural reserves, and national parks. Al-Huwaimiliyah dune field requires more scientific attention because its location is adjacent to infrastructure services, roads, and the urban environment. Mitigation methods could be employed to control dune erosion in Al-Huwaimiliyah dune field via the planting of vegetation in a belt around the dune field. Windbreaks and artificial fences can reduce the wind velocity as well and thus prevent sand dunes from encroaching into urban environments.

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Data Availability Statement

All data used in this research is available per request. The authors will provide any data needed for researchers to expand the work on sand dune evolution in Kuwait.

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