Journal of Geographic Information System, 2025, 17(4), 220-251
https://www.scirp.org/journal/jgis
ISSN Online: 2151-1969
ISSN Print: 2151-1950

Sand Dune Characteristics and Migration in the South of the Jal Al-Liyah Area, Kuwait

Ebrahim Mohammed[1], Adeeba Al-Hurban[2]

[1]Ministry of Electricity and Water and Renewable Energy, Kuwait City, Kuwait
[2]Department of Earth and Environmental Sciences, Kuwait University, Kuwait City, Kuwait
Email: Rsgis1993@gmail.com, adeeba.alhurban@ku.edu.kw

How to cite this paper: Mohammed, E. and Al-Hurban, A. (2025) Sand Dune Characteristics and Migration in the South of the Jal Al-Liyah Area, Kuwait. *Journal of Geographic Information System*, **17**, 220-251.
https://doi.org/10.4236/jgis.2025.174011

Received: May 11, 2025
Accepted: August 19, 2025
Published: August 22, 2025

Abstract

Kuwait's desert area is considered among the arid-hyper arid desert areas in the Arabian Peninsula. The prevailing wind direction in Kuwait is the northeastern, locally known as "Al-Shamal", which is mainly responsible for erosional and depositional activities, yielding the creation of sand dunes in the northwest and west parts of Kuwait. The aim of this study is to observe and monitor the main characteristic features of sand dunes, such as morphology, migration, and mineralogy, located in the southern part of the Jal Al-Liyah area by using a remote sensing approach during the period from 1993 to 2023. Two methods were used to study the migration rate and the change in shape and size, and four methods were used to study the mineralogy of the dunes (QCC Map, NDSDI index Map, ASTER Map, and Fe^{3+}-based map). The results showed a dramatic change in shape, size, and number of the dunes in the area, with a migration rate of 4 m/yr to 60 m/yr. Moreover, the results showed that the sand dunes are basically composed of quartz and carbonate in different percentages within the study area.

Keywords

Sand Dunes, Jal Al-Liyah, Morphology, Mineralogy, Migration, Remote Sensing

1. Introduction

Remote sensing is a key tool in assessing the dynamics and potential of arid regions considered remote, logistically challenging, and physically harsh. Despite these difficulties, arid territories focus on valuable deposits, hydrocarbons, evaporite, minerals, and objects of early human culture since age and dryness preserve virtually everything. Remote sensing provides an essential method of studying such environments without physically needing access, which is especially beneficial in regions where fieldwork cannot be accomplished [1].

This technology uses many instruments on board an orbiting satellite for radar sensing, optical, and thermal sensing, respectively. On the other hand, imaging systems such as radar produce their own electromagnetic energy to enable them to work at any time and in any weather. Such systems have been most beneficial in obtaining information within usually scanty areas due to sitting on loose and dry sand, such as river channels, faults, and other intrusive geological features. Some of the earlier practical uses include synthesizing the Shuttle Imaging Radar System (SIR-A), which was used in the Columbia space shuttle in 1981 to map the concealed fluvial geomorphologies in the western desert of Egypt and Sudan [2]. It was reported that such radar rivers revealed a central Paleolithic river system in Africa that existed millions of years ago, enabling data collection on water supplies and archaeological structures. While remote sensing is a powerful tool, spatial and temporal resolution trade-offs must be carefully considered when selecting sensors for a specific application. No single system offers perfect resolution in both domains, and hybrid approaches (e.g., combining satellite, aerial, and drone data) are often needed for optimal results.

Desert sand seas, or ergs, are large areas of aeolian sands that account for approximately 95% of all sand in deserts. Of all the constitutive factors of desert landscapes, old-world sand seas are more conspicuous in the Sahara, Arabia, Central Asia, Australia, and South Africa. Although these formations are extensive, they occupy 20% - 45% of the surface part of these areas, depending on the degree of classification of desert areas [3]. The mobility of sand and dust in these deserts poses questions about how to manage and utilize them for environmental purposes, especially where they can highly affect Kuwaiti urban and industrial life, agriculture, and infrastructural expansion. This study defines and justifies the problem of dune detection and migration in Kuwait, outlines the study's research questions and hypothesis, explains relevant terms and definitions, and presents the study's scope and limitations.

Both mobile dunes and dust are significant hazards in arid and semi-arid parts of the world [4]. Because of Kuwait's geographical location, it is facing these kinds of hazards, due to the country's location in the Arabian Peninsula with extensive flat desert plains, dune activity occurs, which poses threats to agriculture, developmental urbanization areas, communication interferences, and disruptions of infrastructural development. Windborne sands cause dunes to form and grow in size, which can be dangerous to the stability of structures and affect transport systems [5].

Due to its location, Kuwait's climate is affected by changes in weather and an increase in strong winds. During summer, the temperature reaches 50 degrees Celsius. Rainfall is scarce and unpredictable in Kuwait, with a precipitation of 115 millimeters. The prevailing wind direction comes from the northwest, making up 60% of all winds in Kuwait [6].

The frequent winds (**Figure 1**) from the northwest are cool in winter and spring and hot in summer. The Al-Shamal, common during June and July, causes dramatic sandstorms. These winds result from pressure differences between the subtropical high-pressure systems and low-pressure areas over the Arabian Peninsula.

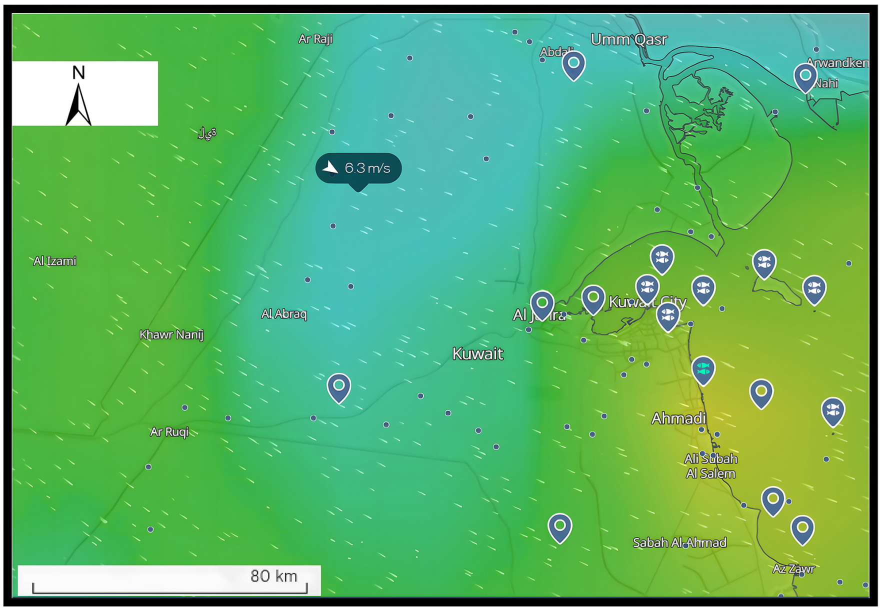

Figure 1. Dominant wind direction in Kuwait [7].

However, knowledge of dune behavior remains limited, so these and other phenomena, despite their environmental and socio-economic importance, still need to be sufficiently studied in Kuwait. Unfortunately, prior research has not investigated further enhanced remote sensing procedures and indices to detect and evaluate sand movement proficiently. This research will seek to fill this research gap by focusing on satellite imagery and indices for actionable suggestions on containing the effects of dune intrusions on Kuwait's emergent and natural landscapes.

This study significantly contributes to accurate environmental management by increasing awareness of dune movement. This helps policymakers formulate and execute ethical measures to control desertification and the risks contributing to sand mobility. Likewise, the results raise pragmatic concerns for urban development, directly providing developers with the knowledge required for constructing infrastructure to withstand the dynamics of mobile sand and accumulation. From the viewpoint of scientific literature, the investigation constitutes a scientific advance by contributing knowledge in remote sensing applications. In particular, it focuses on the efficiency of spectral indices, including Normalized Difference Sand Index (NDSI), the Normalized Sand Index (NSI), and the Normalized Difference Enhanced Sand Index (NDESI), in sand detection and substantiates the need for their application in arid areas.

Many indices can be employed to observe and monitor surface features in remote sensing, such as the normalized difference vegetation index (NDVI), bare soil index (BSI), normalized difference built-up index (NDBI), and soil-adjusted vegetation index (SAVI). While these indices are useful for general land cover classification, they lack the specificity required for detailed sand dune characteristics and migration tracking. NDVI and SAVI are primarily vegetation-focused and perform poorly in sparsely vegetated deserts. NDBI is optimized for detecting urban features. BSI can distinguish between bare soil and vegetation, but cannot effectively differentiate dune sand from other non-vegetated surfaces like dry lakebeds or rocky terrains.

Finally, the study contributes to promoting sustainable development in Kuwait. The results of this research are integrated into Kuwaiti initiatives to realize economic growth with minimal negative impact on the environment. The information derived will be helpful in proposing practical solutions to address the impacts of mobile dunes for better interaction with the landscapes.

Dunes are steadily shifting in Kuwait, and the primary objective of this research study is to identify and evaluate the migration of dunes using remote sensing. It uses satellite images, spectral ratios, and mineralogical studies to find areas containing high sand content using indices, including NDSDI, NDESI, and NSI, as they have proven to have an efficient ability to detect dunes. *In situ* data was missing because of time and cost limitations. It investigates various changes that occur in the movement of sand to identify environmental and/or climatic parameters that cause the changes in sand movement.

In Kuwait, the prevalence of fine-grained, rounded, well-sorted quartz sands contributes to the formation of barchan dunes, which are highly mobile under strong winds. Kuwait's desert experiences low humidity, meaning dunes composed mostly of quartz remain dry and mobile, making them susceptible to wind-driven migration. Kuwait's Al-Shamal winds interact with the mineralogical composition of dunes, shaping their movement across highways and oil fields.

The operational implications of dune migration in the Jal Al-Liyah region are significant for urban planning, transportation infrastructure, and energy development. The empirical findings of this study, particularly the identification of dominant dune types, migration rates, and prevailing wind directions, can directly inform land-use planning and infrastructure placement. For example, recognizing the orientation and mobility of barchan and linear dunes in this area enables planners to avoid placing critical infrastructure, such as pipelines or roads, in high-mobility corridors. Furthermore, using the NDSDI and ASTER-based maps, areas of active sand accumulation can be forecast, allowing for proactive mitigation strategies like sand fences, vegetation barriers, or rerouting of transportation lines. Given that Jal Al-Liyah is located near oil and gas fields and is increasingly subject to development pressures, integrating geomorphological data into environmental impact assessments and planning documents can reduce maintenance costs and extend the operational life of infrastructure exposed to aeolian hazards. Thus, the results of this study are not only scientifically robust but also offer practical guidance for sustainable development in arid regions.

General health-wise, studies showed that mineral components such as calcite and quartz can possess adverse impacts on public health. For example, Al-Hurba and Alostad (2009) [8] conducted a study on the textural characteristics of dust fallout and the potential effect on public health in Kuwait City and suburbs, which showed that humans in different sites of Kuwait are being exposed to different ranges of concentrations of minerals such as calcite, quartz, albite, dolomite, and gypsum. Inhalation of calcite may result in coughing and sneezing, nasal irritation, and, in cases of chronic exposure, may result in alkalosis and hypercalcemia. Quartz has the potential to cause serious impacts on the respiratory system following prolonged exposure. The study found that, compared with international and local standards, it is highly likely that the harmful and hazardous effects of long-term exposure to dust fallout on the human body are being experienced by long-term exposure to dust fallout in Kuwait.

By understanding the mineralogical composition of sand dunes, scientists and environmental planners can predict their movement, manage their impact on infrastructure, and develop stabilization strategies in regions like Kuwait, where shifting dunes threaten roads and settlements. Therefore, one of the main objectives of this study is to determine the distribution of the minerals, specifically hematite and ferric/ferrous iron oxides, to identify a relationship between these mineral concentrations and dune behavior.

Two major factors that are increasing the amount of sediment available for transport and thus accelerating the formation of dunes are: 1) disruption of the desert pavement in Kuwait due to Gulf War activities, and 2) diversion of the Tigris River channel system to drain the marshes in southern Iraq (**Figure 2**).

Dunes in Kuwait are located in several areas. One of these areas, which is considered to be the major area for aeolian formation, such as dunes, is Jal Al-Liyah, which is located in north-north-western Kuwait, between 29˚30'N to 30˚N and 47˚30'E to 47˚E (**Figure 3**). It encloses a major dune field (Al-Huwaimiliyah) that trends from northwest to southeast and covers approximately 220 km^2.

This research aims to study the characteristics of the sand dunes in the southern part of Jal Al-Liyah over the past 30 years, in terms of morphology (shape and size) changes, the rate of movement (migration), and mineralogy.

While this study focuses on the migration patterns and geomorphological features of sand dunes in Kuwait, the findings hold broader relevance when interpreted within the larger aeolian system of the Arabian Peninsula. Kuwait's dunes, particularly those in areas like Al-Huwaimiliyah and Jal al-Zur, are not isolated but form part of a continuous sediment transport corridor extending from the Ad-Dahna Desert in Saudi Arabia. The wind regimes, sediment composition (quartz-rich with iron oxide coatings), and dune morphologies in Kuwait are similar to those in vast arid regions such as the Rub' al-Khali and the eastern An-Nafud.

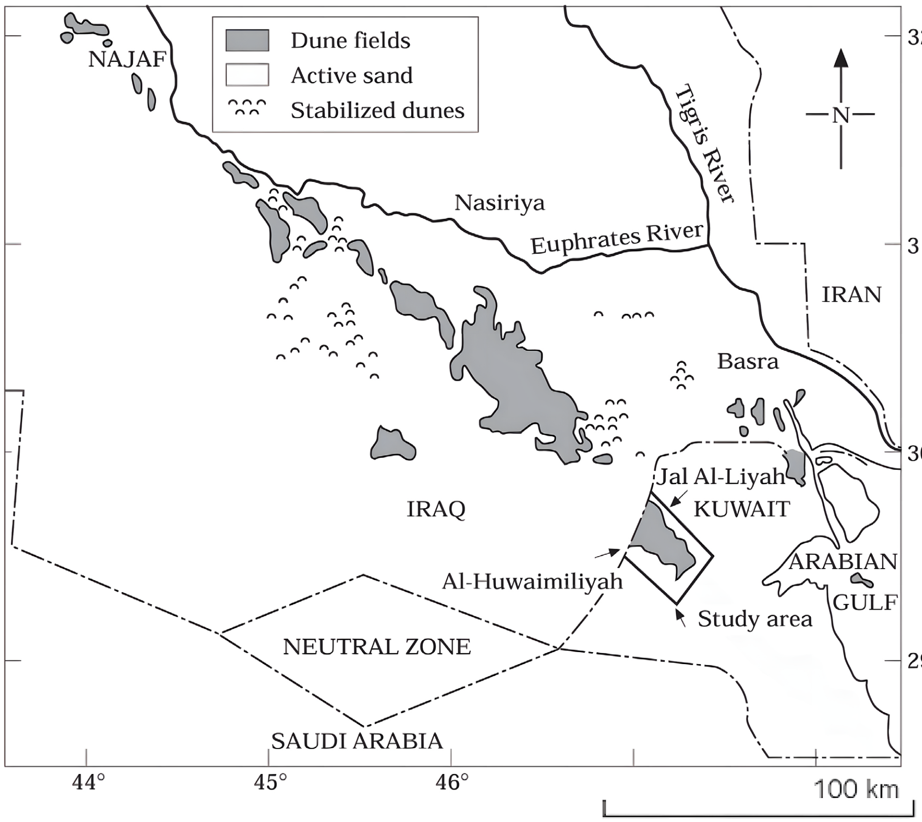

Figure 2. A map of the dune fields in Kuwait [9].

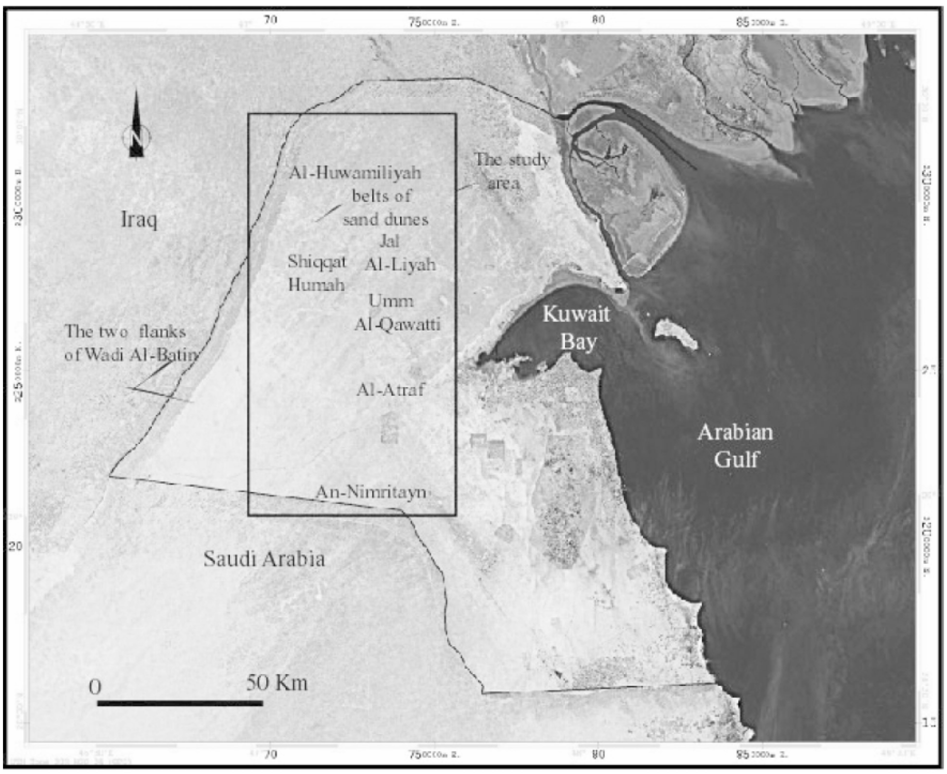

Figure 3. A satellite image of the dune fields in Kuwait [9].

1.1. Literature Review

Sediment movement, known as aeolian activity, is the result of wind energy and controls the geography of dunes and coasts around the world today [10]. Knowledge of these migration patterns is important because they negatively affect crops, buildings, and water sources [11]. Scientists use direct and indirect methods to investigate the phenomena of dune movement, using field and airborne research methods.

The mineralogical composition of sand dunes significantly influences and directly contributes to their mobility and behavior, influencing their formation, movement, stability, and response to environmental changes. Grain composition, size, sorting, mineral stability, grain shape and surface texture, mineral cohesion and moisture retention, color and heat absorption, and wind erosion and deposition patterns collectively affect how dunes respond to wind and environmental conditions [12]-[15]. Quartz-rich dunes tend to be highly mobile as quartz is hard, resistant to weathering, and does not easily bind with moisture, whereas carbonate-rich dunes may be more cohesive due to chemical interactions with moisture, making them less mobile, and gypsum dunes, found in some desert environments, tend to be more compact due to their tendency to absorb moisture and crystallize. Some minerals, such as clays and carbonates, can bind sand grains together when exposed to moisture, reducing dune movement. In coastal and semi-arid environments, mineral cements like calcite can solidify dunes, forming stabilized dune ridges [15].

Dunes composed of well-sorted, fine to medium sand grains are typically more mobile. In the Abshirin Erg, studies have shown that such dunes are fully active, with their mobility closely linked to grain size distribution and sorting. Poorly sorted sands with a mix of grain sizes tend to be more stable due to increased interlocking between particles, which impedes movement [13]. Rounded grains (common in quartz-dominated dunes) reduce friction and allow dunes to shift more easily. Angular grains (more common in freshly weathered rocks) resist movement because they interlock. Polished or frosted grains, often found in desert dunes, indicate prolonged wind abrasion and enhance dune mobility [15].

The durability of minerals under weathering conditions also affects dune mobility. Quartz-rich dunes, composed of mechanically and chemically stable grains, are more likely to remain active over time. In contrast, dunes containing unstable minerals like feldspars may experience rapid weathering, leading to consolidation and reduced mobility. For instance, studies in North America and Africa have demonstrated that mineralogical maturity, characterized by a high quartz content, correlates with increased dune activity [12] [14].

The presence of heavy minerals, such as magnetite, can influence dune color and thermal properties, which in turn affect moisture retention and cohesion. Darker dunes with higher heavy mineral content may absorb more heat, leading to drier and more mobile conditions. For example, the Great Sand Dunes National

Park exhibits dark patches due to magnetite concentrations, impacting the local thermal regime and sand movement [15].

Dark-colored minerals (e.g., magnetite or heavy minerals) absorb more heat, causing thermal expansion and increased wind erosion, whereas light-colored quartz and feldspar reflect more sunlight, keeping the sand cooler and less prone to thermal cracking [15]. Mineralogy affects how dunes respond to wind forces, as harder minerals (quartz) resist breakdown, leading to long-lived dunes, whereas softer minerals (feldspar, calcite) weather more easily, creating finer dust that may be carried away, leading to landscape changes [15].

Earlier conventional techniques include monitoring dune shifting using permanent reference points and undertaking topographic surveys using clinometers and tapes [16]. Another technique that can be conducted with ground measurements is registering or trapping active sand grains with sensors or traps on the dunes' surface [17].

Remote sensing is a more time- and cost-efficient approach for investigating dune mobility, allowing large regions to be studied from a distance. The aerial photographs offer important information about the dynamic processes of dunes, migration, and morphological evolution [18].

Kuwait has a high activity of aeolian processes (deflation, transportation, and deposition), which are associated with the country's hot, dry, and windy environment, the bedrock's detrital composition, and its location downwind from the Mesopotamian floodplain's high-deflational area. Because the loose mobile sediments cover at least 35% of Kuwait's desert surface,

These sediments are constantly carried by the wind along the surface to produce various landforms, including dunes. In Kuwait's northeast, the latter are the most prevalent aeolian landform [6].

In Kuwait in 1972, this wind usually carried dust and fine sand particles in suspension, causing dust and sandstorms with speeds reaching between 6 - 7 ms^{-1}. As long as the northwest Shamal winds persist, fresh dunes will continue to build, while older ones swell because of the greater quantity of sand that may be transported (**Figure 4**). The dune field of Al-Huwaimiliyah (mostly barchan dunes) consists of more than 2200 dunes, which together cover approximately 60 - 70 km^2, and the dunes vary in size from 150 - 200 m long, 3 - 4 m high, and 25 - 35 m in width [9].

Mapping and monitoring were the methodologies used by [9] to study the sand dunes in Kuwait. For mapping, 110 aerial photographs were used and digitized to create a cover sheet to cover the study area. For monitoring, he conducted field observations to examine and compare the information from the imagery.

Moreover, [19] aimed to identify the change in the number and position of the sand dunes in the northwest part of Kuwait using Landsat imagery to compare the changes before and after the Gulf War. They used image-enhancement techniques. They found an increased rate of dune formation due to the war (**Figure 5**).

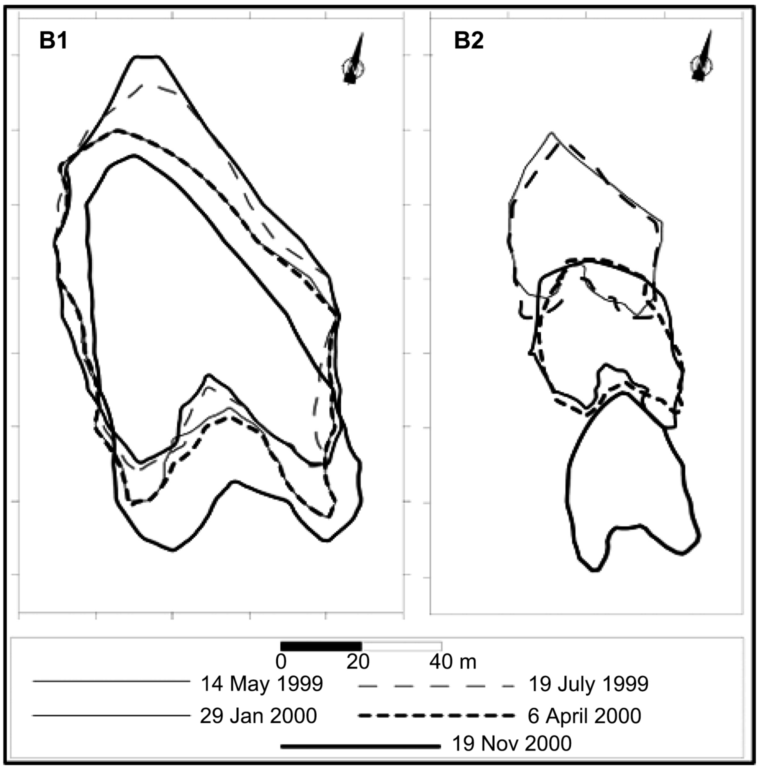

Figure 4. Monitoring a dune [9].

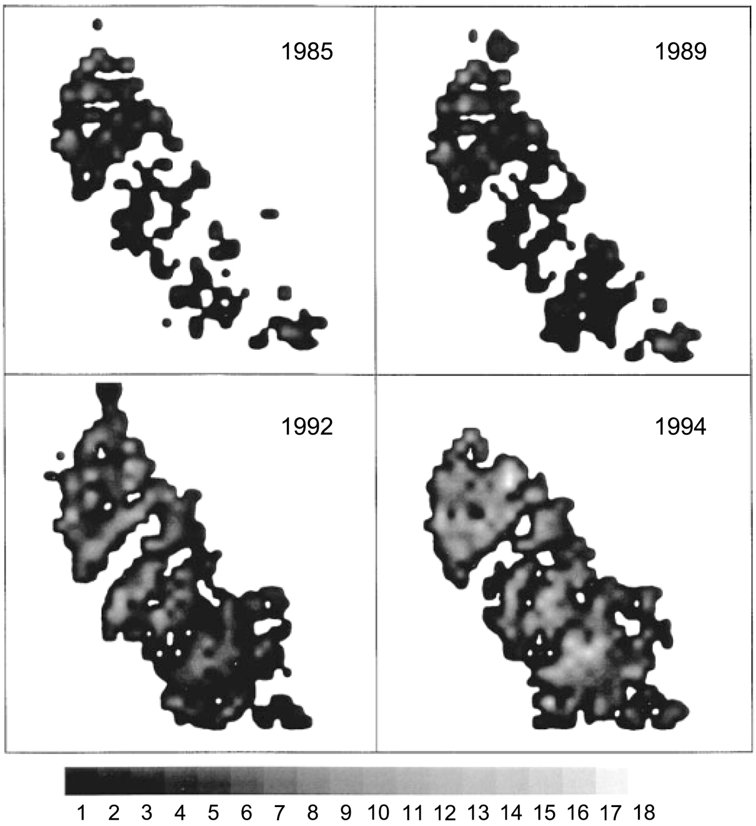

Figure 5. Dune density maps [19].

The hypothesis that NDSDI and NDESI are practical tools for identifying and assessing dunes in Kuwait was tested in this paper, and the findings support the hypothesis and previous studies. Both indices use sand's differential spectral properties, especially in the visible, NIR, and SWIR domains, to separate sand from other land cover types. For instance, the NDSDI, which quantifies sand movement and dynamics, has been used extensively in arid regions; the coefficient provided a high level of accuracy in identifying and monitoring dunes.

The NDESI is a suitable approach for extracting sand features in arid and hyper-arid zones. In Kuwait, these indices were proven to give correct spatial distribution and movements of the dunes, as has been evidenced by studies that have been done in other deserts like the Saharan and Arabian deserts, where these indices have been tested by [20]. The use of Landsat and ASTER imagery also strengthens the argument for these indices since they are rightly applied to the spectral compositing ability of these satellites to improve the identification of sand-covered zones. Based on the study's results and conformity with previously published works, the hypothesis is valid.

Remote Sensing is a key tool in assessing the dynamics and potential of arid regions considered remote, logistically challenging, and physically harsh. In spite of these difficulties, arid territories focus on valuable deposits of hydrocarbons, evaporites, minerals, and objects of early human culture, since age and dryness preserve virtually everything. Remote Sensing provides an essential method of studying such environments without physical interaction, which is especially beneficial in regions where fieldwork cannot be accomplished.

This technology uses many instruments on board an orbiting satellite for radar sensing and optical and thermal sensing, respectively. On the other hand, imaging systems such as radar produce their own electromagnetic energy to enable them to work at any time and in any weather. Such systems have been most beneficial in obtaining information within usually scanty areas due to sitting on loose and dry sand, such as river channels, faults, and other intrusive geological features. Some of the earlier practical uses include synthesizing the Shuttle Imaging Radar System (SIR-A), which was used in the Columbia space shuttle in 1981 to map the concealed fluvial geomorphologies in the western desert of Egypt and Sudan [21]. They stated that such radar rivers revealed a central Paleolithic River system in Africa that existed millions of years ago, enabling data collection on water supplies and archaeological structures.

Likewise, the Landsat program began in 1972 and has brought about significant changes in mapping and studying desert regions. Based on the Multispectral Scanner (MSS) and Thematic Mapper (TM) sensors, Landsat satellites collect data from different segments of the electromagnetic spectrum, allowing them to identify specific minerals and features.

The lack of vegetation in arid lands helps improve spectral remote sensing since mineral compositions like limonite may be spotted on satellite imagery. False color composite generation capability also enriches analysis, where we have vibrantly red colors, such as healthy vegetation, suitable for environmental and resource mappers.

As has been noted, remote sensing has not only exploration benefits in regions characterized by arid climates. It helps to identify the location of placer minerals and contributes to the study of the resulting paleogeography. Using radar and spectral imaging, academic researchers can gather valuable information to help manage resources and plan urban development in such extreme environments despite their important locations.

1.2. Study Area

The state of Kuwait lies in the northwest zone of the Arabian Gulf with a total area of about 17,818 km^2 and coordinates of longitude 46˚33' and 48˚36'E and latitude 28˚30' and 30˚05'N. Iraq surrounds it to the north and west, and Saudi Arabia to the south (**Figure 6**). The geographical location of Kuwait within a desert area and geological/geographical considerations profoundly affect dune formation and migration [22].

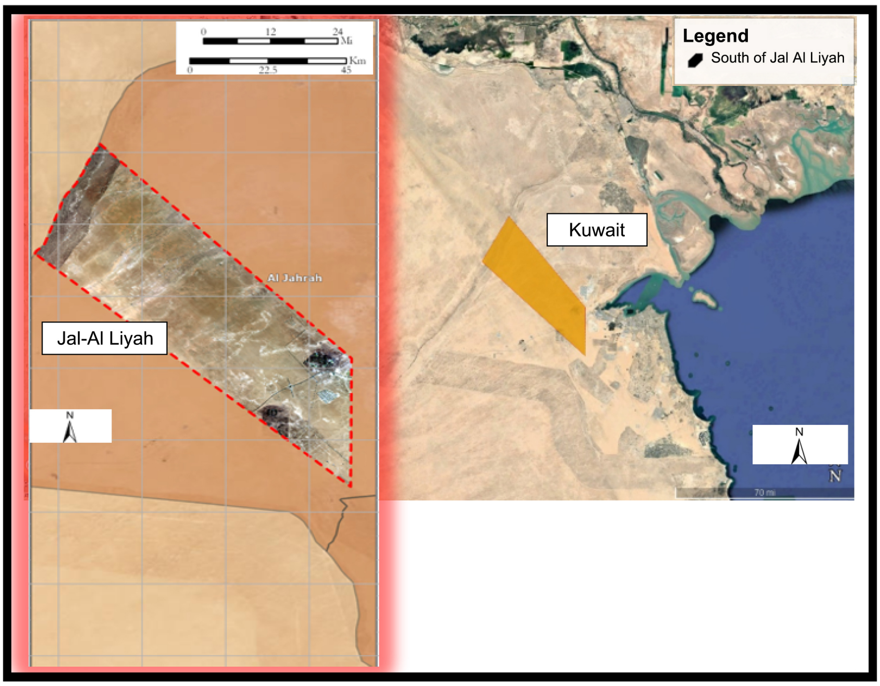

Figure 6. Study area of Jal Al-Liyah.

Southern Jal Al-Liyah (29˚33'02"N, 47˚17'32"E) in the western part of the Kuwait desert contains many dune patterns, which will be focused on in this study. Desert landforms, like dunes, occupy large areas of Kuwait, though they are predominantly located in the country's western part. Barchan, domal, and nabkha dunes, sand sheets, and sand drifts have been the most investigated Aeolian formations.

Aeolian deposits were classified by [22] into four categories. In addition, a detailed dunes map of the Al-Huwaimiliyah region was produced using image interpretation techniques and satellite imagery. This study shows that sand movement is a menacing factor to infrastructure, croplands, and inland areas, hindering future growth.

Kuwait's climate aggravates these problems. Frequent sand and dust storms involving the deflation of surface materials indicate the continuing activity of the sand belt in the area. Mobile sand affects the road system, development operations, and land utilization, especially in Al-Huwaimiliyah and Al-Atraf, as depicted in the literature by [21]. Knowledge of sand movement has been founded on baseline conditions of Kuwait's surface geology [23].

2. Materials and Methods

Figure 7 shows a flowchart summarizing the workflow during the construction of the study.

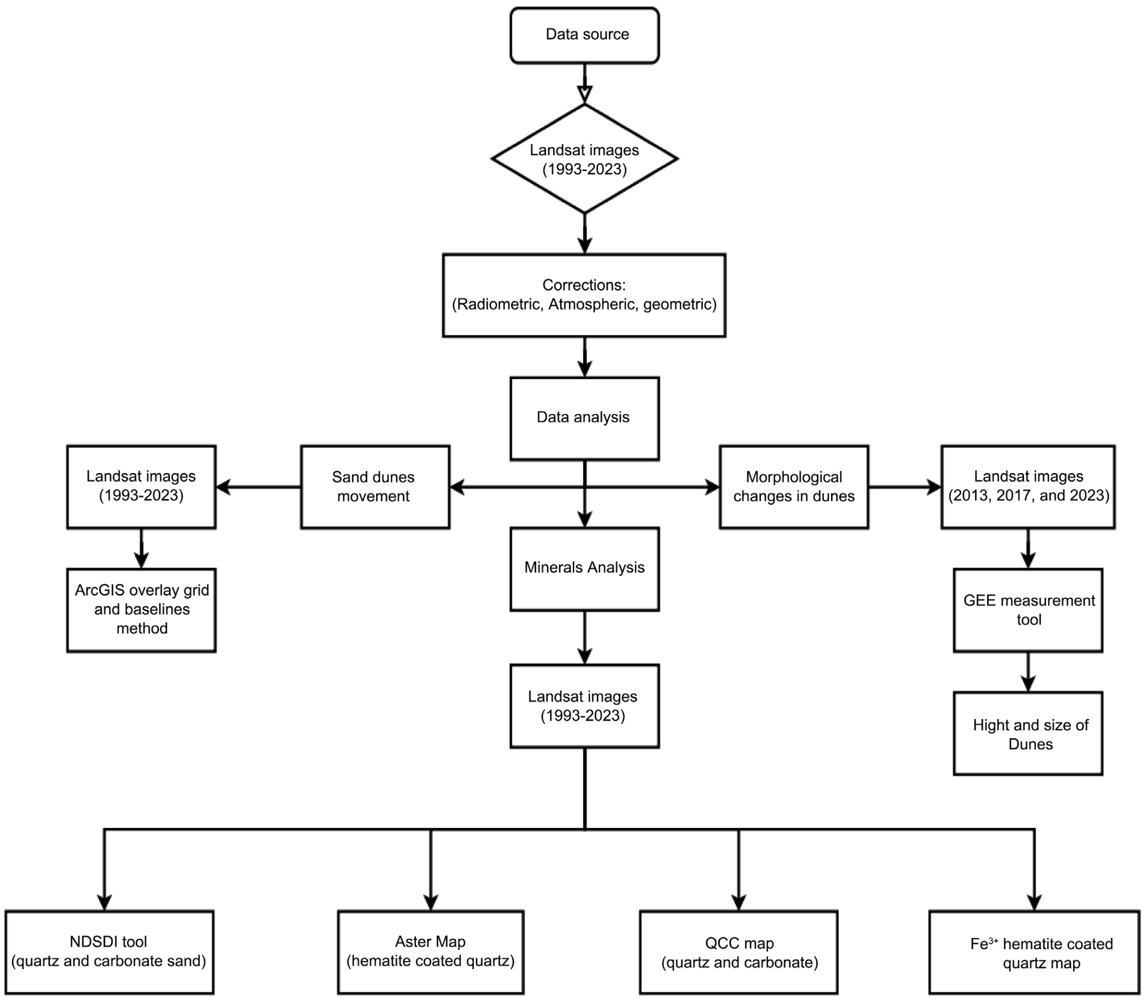

Figure 7. A flowchart showing the workflow adopted during the implementation of the study.

2.1. Data Collection

In remote sensing, sand detection has become significantly advanced with the development of spectral indices, which can detect sand from other land cover types

(Table 1). Indices like the Normalized Difference Sand Index (NDSI), the Normalized Sand Index (NSI), and the Normalized Difference Enhanced Sand Index (NDESI) have been applied due to their ability to enhance sand features in spectral imagery. By utilizing the spectral contrast between shortwave infrared (SWIR) and visible bands, the NDSI index detects sand among vegetation and water bodies. Also, the NSI index uses the reflectance properties of both near-infrared (NIR) and visible bands to enhance the detection of sand. Moreover, the NDESI index integrates additional spectral information to reduce the noise (unwanted reflectance) from other surfaces to detect sand. The Normalized Difference Sand Dune Index (NDSDI) is derived by incorporating elements from NDSI, NSI, and NDESI to improve the accuracy of sand dune detection. It uses a combination of SWIR, NIR, and visible bands which are required to detect and monitor sand.

Table 1. Classification indices.

Index	Sand Detecting Range
NDSI (L5)	High values
NSI (L5)	High values, close to 1
NDESI (<L5)	Close to 2
NDSDI	Typically, 0.2 to 1 for sand dunes.

Normalized Difference Enhanced Sand Index (NDESI) is the most suitable for arid and hyper-arid regions. However, red-edge bands (SWIR 1 - 2, having 1.57 to 2.29, respectively) are unavailable with the wide spectrum band of B7 or mid-infrared on L5 and L7 (Range: 1.55 - 1.75, respectively).

$$=\frac{(b4-b2)}{(b4+b2)}+\frac{(b7-b6)}{(b7+b6)}$$

where b2: Green band, b4: Near-infrared band, b6: Thermal infrared band, and b7: Shortwave infrared band.

Normalized Differential Sand Dune Index (NDSDI) (dry) is appropriate.

$$=\frac{(R-SWIR2)}{(R+SWIR2)}$$

where R: band 3 (Red), SWIR2: shortwave infrared 2.

NDSDI is derived by comparing the reflectance in the Short Wave Infrared (SWIR) and Visible bands, pinpointing sand-dominant regions using the spectral behavior of sand.

NDSDI is used to detect and quantify sand mobility with an important focus on active aeolian deposition zones.

NDESI assesses aeolian sand accumulations by including several spectral bands to distinguish fine sand grains from other materials.

These indices were derived using a geographic information system and the ENVI software, since these two provide enhanced geospatial analysis and better handling of the spectral bands.

The study aims to observe and assess the changes in the sand dune morphological features in the western region of Kuwait using remote sensing data from 1993 to 2023. Additional important satellite datasets are Landsat 5, 7, and 8, as well as ASTER imagery in Table 2, which offer relatively high-resolution multispectral and thermal information about the sites that is valuable for Aeolian activity study. These datasets, with parallel temporal coherence and spectral acquisition, enable the documentation of the spatial dynamics of the dune fields, their mineralogical character, and movement patterns.

Table 2. Data classification.

Landsat (5, 7, 8, and 9)						
Image Year	Path	Row	Acquisition Date	Format	Landsat Platform	Study Area
2023	166	40	7/30/2023	TIFF	**9**	**2047.67 Sq Km.**
2018	166	38	6/24/2018	TIFF	**8**	
2013	166	40	6/30/2013	TIFF	**8**	
2008	165	40	10/30/2008	TIFF	**7**	
2003	166	38	9/27/2003	TIFF	**7**	
1998	166	38	10/23/1998	TIFF	**5**	
1993	166	39	9/23/1993	TIFF	**5**	

2.2. Data Analysis

2.2.1. Morphological Changes in Dunes

The first phase of the study compares and measures the height and width appearance of the dunes using Google Earth Pro measurement tools, which establish the volumetric and structural changes in the dunes.

2.2.2. Analysis of Sand Dune Movement

The dune migration rate was established through an overlay of a grid on the area of interest and the establishment of the baseline of the temporal data set. This methodology is a very efficient methodological base for researching aeolian processes and predicting areas where aeolian processes can pose a threat.

2.2.3. Mineral Analysis

Spectral analysis was conducted for Hematite and Ferric Iron Oxides, and on particular bands of Landsat and ASTER images. Combining the spectral absorption of hematite in the VNIR and the ferric oxides through the SWIR bands was performed using QCC Map, ASTER mineral maps, and Fe^{3+} based spectral mapping. These analyses permitted the identification of mineral composition in order to discuss the subsequent geologic history and the source of the sediments that formed dunes. Figure 8 shows the digital elevation model map and 3D map of the study area.

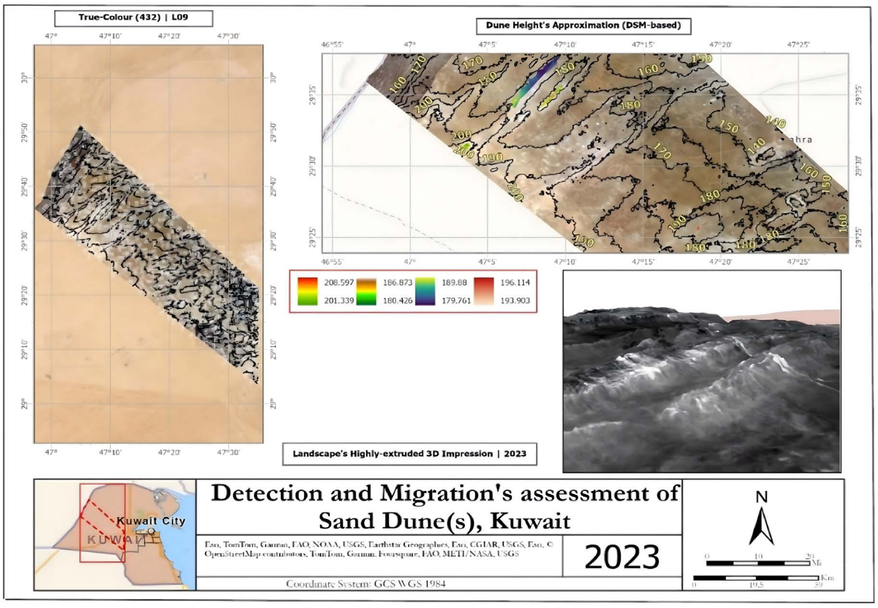

Figure 8. Digital elevation model and 3-dimensional view of the study area.

3. Results

3.1. Dune Morphological Change

Two different areas (A & B) in Jal Al-Liyah were chosen to measure the morphological (shape and size) changes of the dunes. Dune A (29˚41'56"N, 47˚05'57"E) was measured during three different years (2013, 2017, and 2023), while dune B (29˚42'01"N, 47˚12'00"E) was measured during three different years (2013, 2016, and 2023) (Figures 9-11).

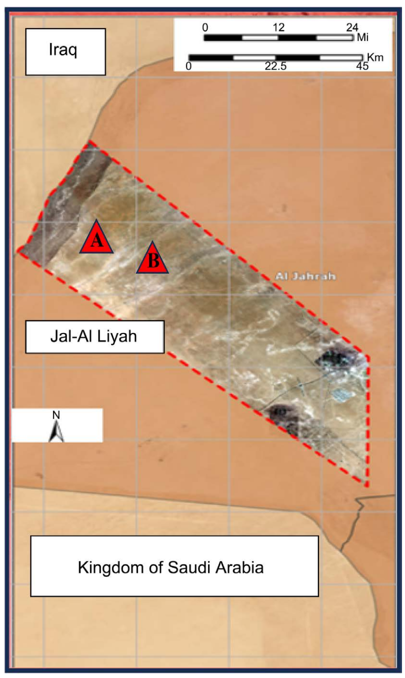

Figure 9. Locations of dunes in the analysis.

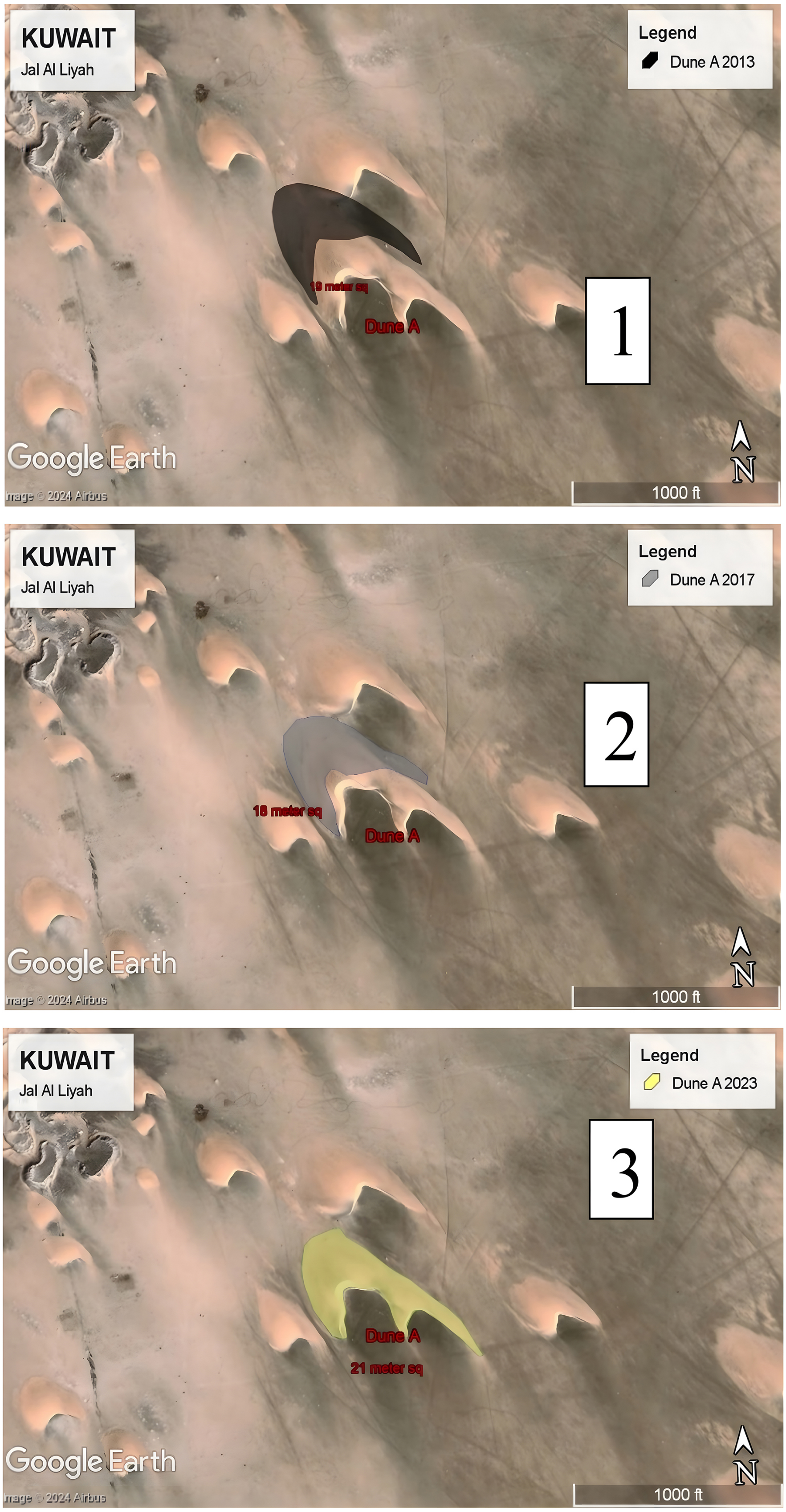

Figure 10. The morphological changes of Dune A during 1 (2013), 2 (2017), and 3 (2023).

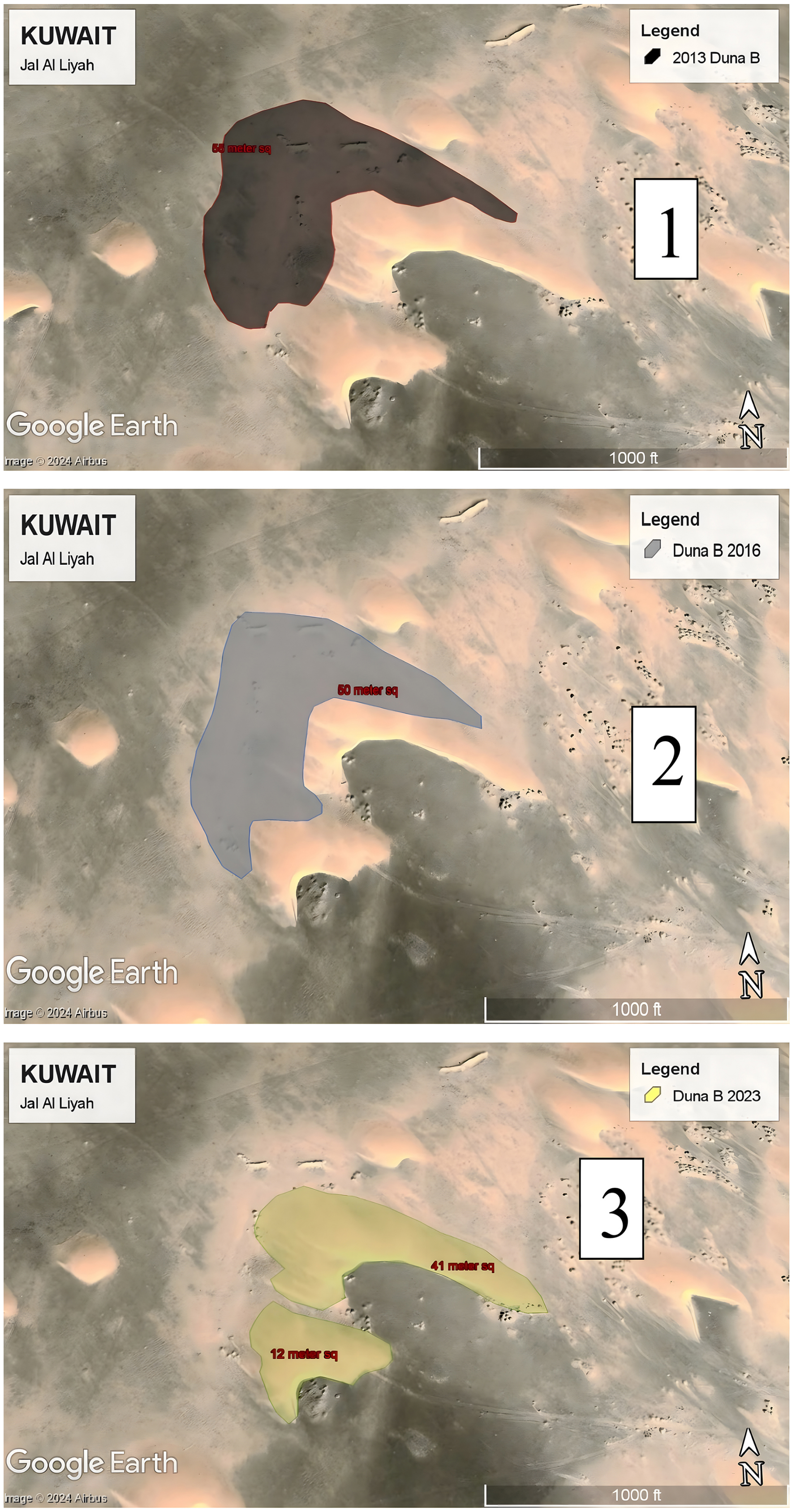

Figure 11. The morphological changes of Dune B during 1 (2013), 2 (2017), and 3 (2023).

3.2. Sand Dune Migration Rates

The analysis depends on setting a fixed point for each period (5 years) and measuring the distances between the dunes and the fixed point using baselines (Figure 12). After that, by measuring the difference between the baselines for each period, we can determine the migration distances.

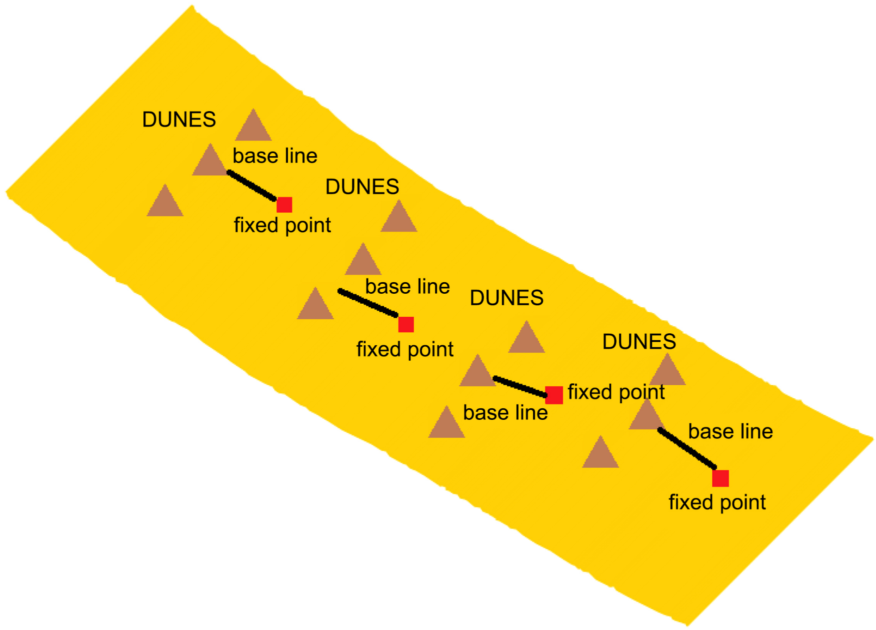

Figure 12. Sketch of the methodology.

Based on the grid measurements, this study quantified the rates of dune movement for the years 1993 to 2023. The migration rates observed when a temporal analysis was done ranged from 4 to 60 meters per year and fluctuated with changing wind strength, wind direction, and the mineralogy of the ocean floor. Year-to-year comparisons of dune positions revealed areas of high differential movement, especially in sloping regions with unstable or sandy deposits. These outcomes amplify how mineral preferences interact with aeolian processes to provide essential information for land utilization and environmental management in arid areas. (Figures 13-16) (Table 3, Table 4).

Table 3. Distances of migration between 1993 and 1998.

ID	Shape	Shifting Distance (Meter)
1	polyline	594.6
2	polyline	419.5
3	polyline	231.48
4	polyline	934.97

Continued

5	polyline	159.8
6	polyline	242.8
Average migration		430.52 “86 per year”

Table 4. Distances of migration between 2018 and 2023.

ID	Shape	Shifting Distance (Meter)
1	polyline	22.2
2	polyline	21.1
3	polyline	31
4	polyline	29.7
5	polyline	17.5
6	polyline	26.3
Average migration		19.46 “3.8 per year”

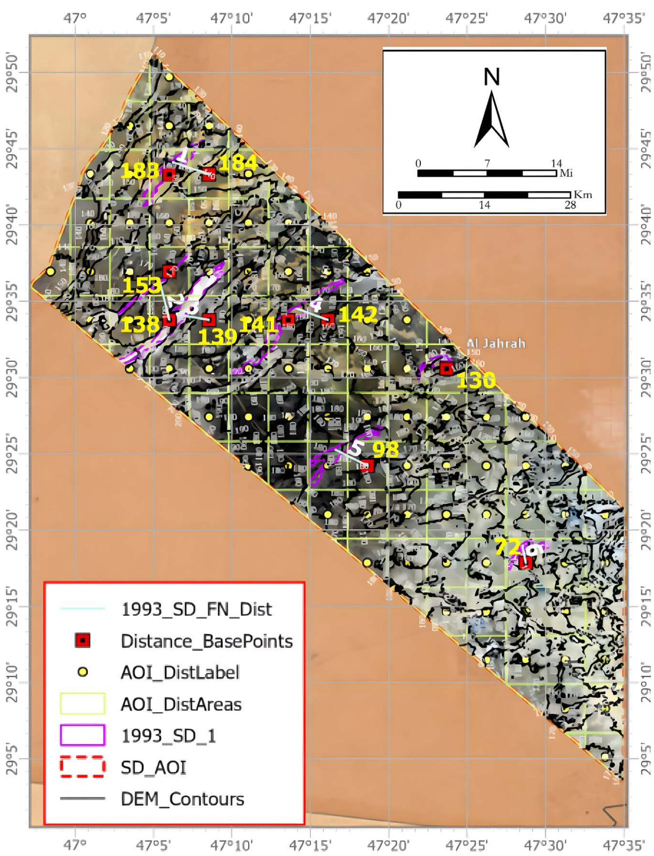

Figure 13. Baseline of the study area in 1993.

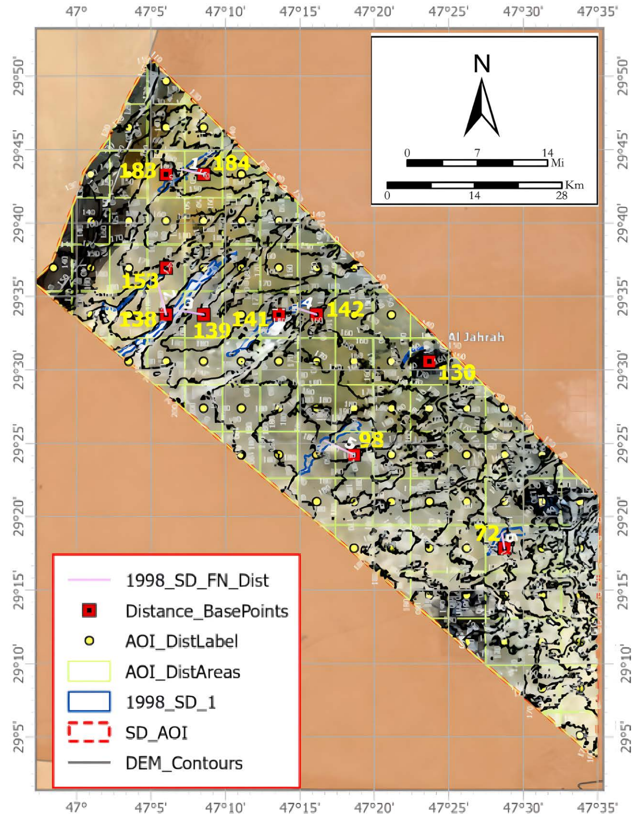

Figure 14. Baseline of the study area in 1998.

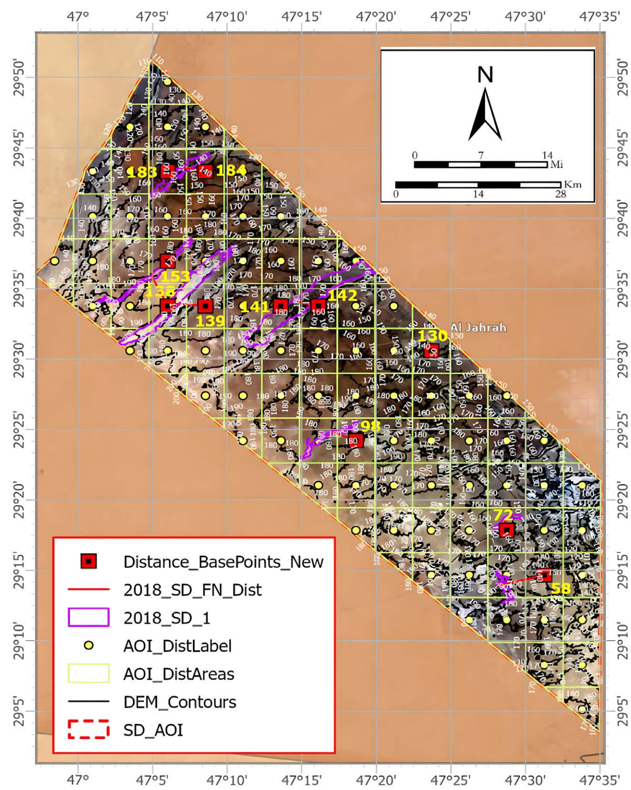

Figure 15. Baseline of the study area in 2018.

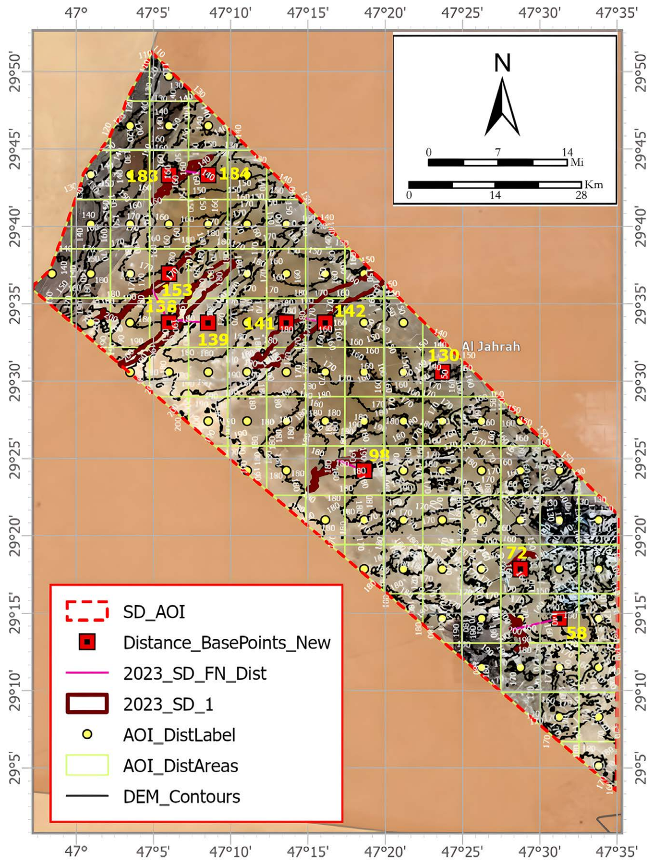

Figure 16. Baseline of the study area in 2023.

3.3. Mineral Identification

Through remote sensing analysis, conclusions were deduced from the QCC Map, NDSDI Index Map, and ASTER Map, and Fe^{3+} mapping was used to identify important minerals influencing dune mobility in the western region of Kuwait. These regions consist of soils rich in hematite and ferric iron oxides. The mineral identification process used spectra from identified mineral specimens and "predicted spectra" computed from the first four PCA components. Hematite with unique absorption features observed from visible and near-infrared (VNIR) spectral bands was used to map AOI. Likewise, the distribution patterns of ferric iron oxides discernible in shortwave infrared (SWIR) bands were quantified. From this publication, QCC integration and Fe^{3+}-based maps provided the opportunity to distinguish areas with high mineral content deposits from areas with scarce mineral deposits in the dune systems. The spatial analysis discovered that hematite and ferric iron oxides are concentrated near certain dune formations, impacting dune dynamics. It was also established that they are geochemically related to metal deposits formed from sedimentary sources and remobilized by wind activity.

3.3.1. NDSDI Index Map

- The NDSDI (Normalized Difference Sand and Dust Index) is used to identify the presence of quartz and carbonate sands as opposed to sands coated with

Fe^{3+} (iron oxide) (**Figure 17**).

- Negative values of the NDSDI indicate a greater presence of quartz and carbonate sands compared to Fe^{3+}-coated sands.
- NDSDI maps rely on the red band, which is used for differentiating sand content from vegetation or urban areas, and the SWIR2 band, which is sensitive to minerals like quartz and carbonate.

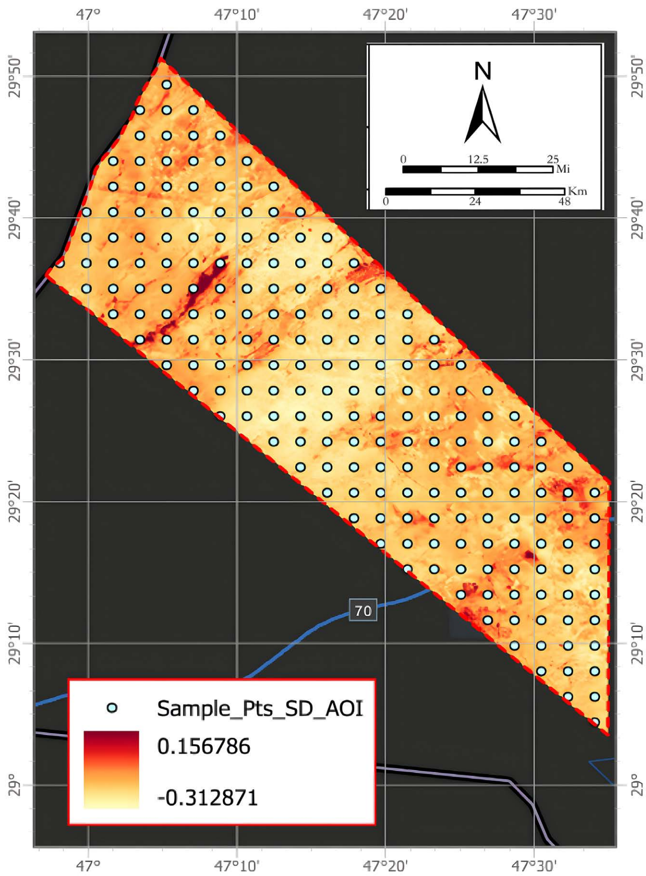

Figure 17. NDSDI in 1993.

3.3.2. Fe^{3+} Hematite-Coated Quartz Map

- This index assesses the presence of Fe^{3+} (ferric iron oxides) coatings on sands using Landsat bands (5, 7, 8, and 9) (**Figure 18**).
- Red (Higher Values): Indicates a higher presence of hematite-coated quartz (strong Fe^{3+} signal), and Green (Lower Values): Represents lower concentrations of hematite-coated quartz or areas dominated by other materials.
- Fe^{3+} Hematite-coated Quartz maps rely on the red band, which captures the reflectance of ferric iron oxides (hematite) that appear reddish. SWIR2 normalizes the reflectance and helps differentiate sand and ferric oxides.

3.3.3. QCC Map (Quartz and Carbonate Sand Content Discrimination)

- The QCC Map (**Figure 19**) provides a clear representation of quartz and carbonate content variations.

- QCC map depending on Band 6 (SWIR 1), which is sensitive to quartz reflectance, and Band 7 (SWIR 2), which is sensitive to carbonate reflectance.
- Low values on the QCC map represent high reflectance associated with carbonate sands, whereas high values indicate high reflectance from quartz sands.

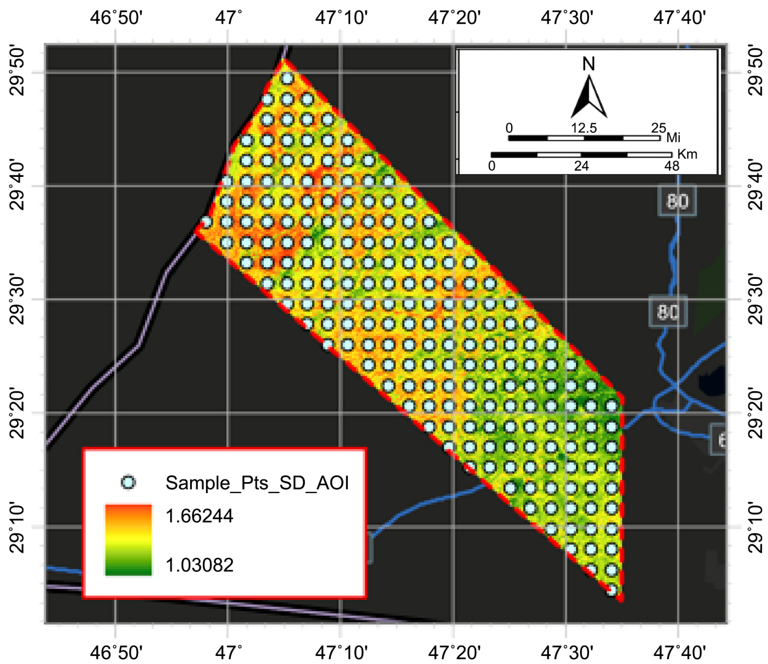

Figure 18. Fe^{3+} hematite-coated quartz index in 1993.

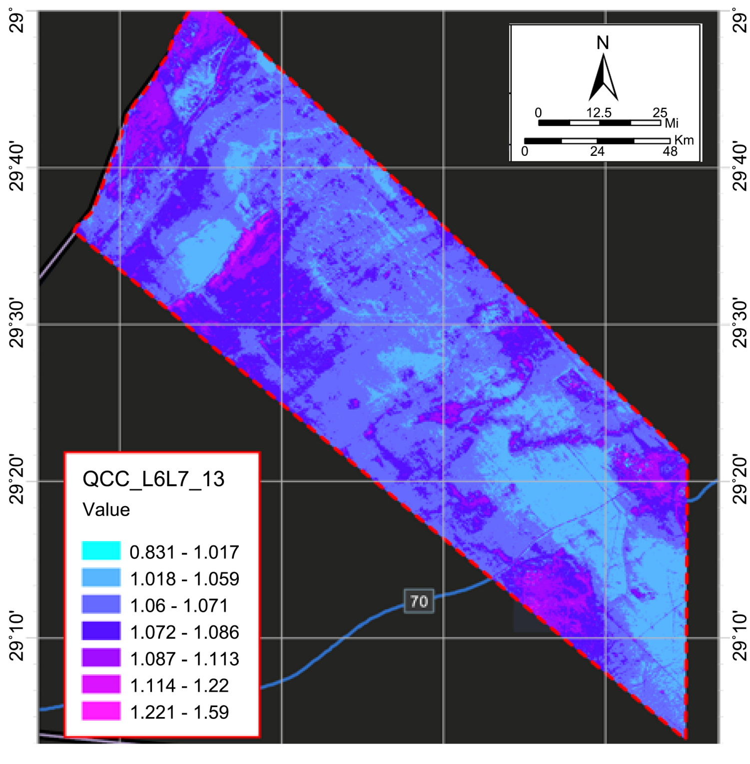

Figure 19. QCC map in 2013.

3.3.4. ASTER Map (Advanced Spaceborne Thermal Emission and Reflection Radiometer)

- Figure 20 and Figure 21 show ASTER maps in 2018 and 2023.
- Indicates that the map portrays regions rich in hematite-coated quartz grains.
- ASTER provides high-resolution imagery in the visible, near-infrared (VNIR), shortwave infrared (SWIR), and thermal infrared (TIR) ranges.
- Yellow (Higher Values): Indicates higher concentrations of hematite-coated quartz grains, reflecting a stronger ferric iron oxide signal, and Purple (Lower Values): Indicates lower concentrations or areas dominated by other surface materials.

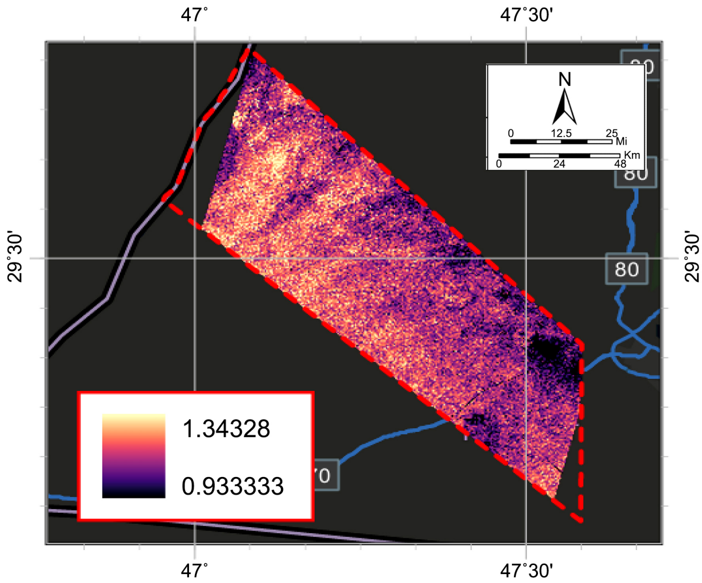

Figure 20. ASTER map in 2018.

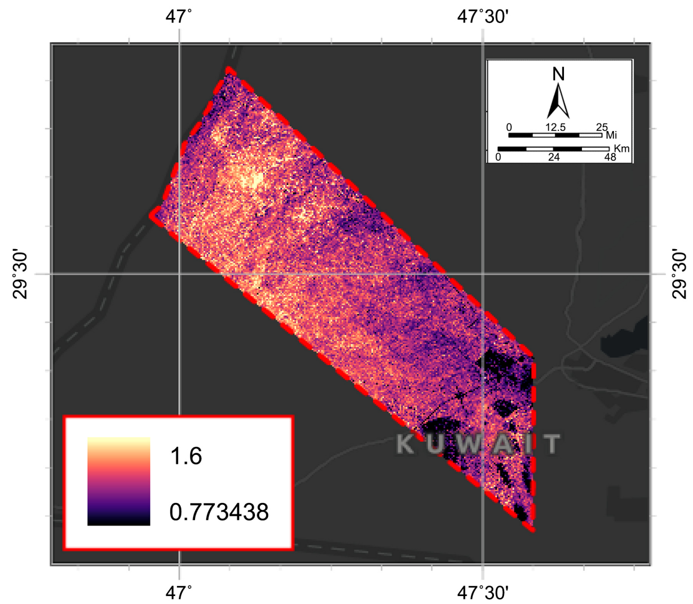

Figure 21. ASTER map in 2023.

4. Discussion

Due to the wind direction, the morphology of the dune pattern in the southwestern Kuwait desert is in active movement by migrating towards the southeast; some dunes lose their size while others become bigger. Moreover, some Barchan dunes have joined other dunes and become Barchanoid, while other dunes have separated into two smaller dunes or disappeared. From 2013 to 2023, Dune A has changed from a Barchan dune to a Barchanoid dune, and its size increased by 2 square meters. On the other hand, from 2013 to 2023, Dune B has separated from 55 meters into two barchans, 12 square meters and 41 square meters, as shown in Figure 22 and Figure 23.

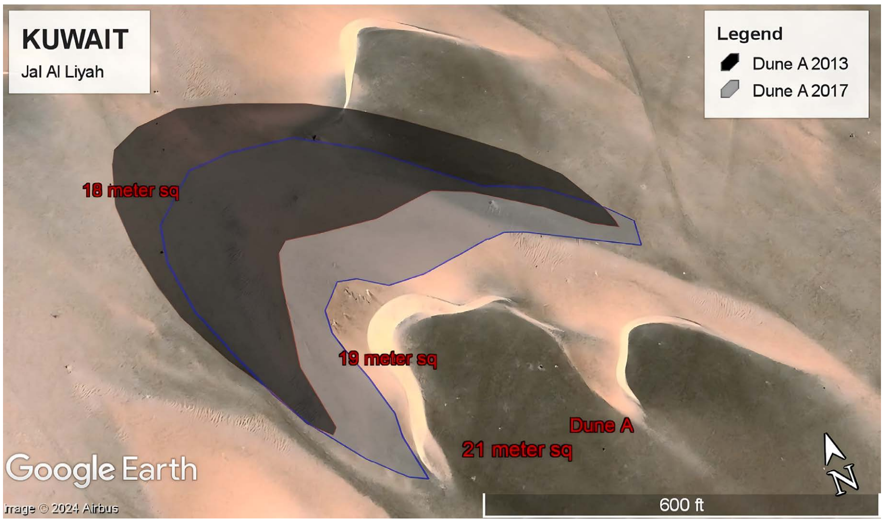

Figure 22. Morphological changes of Dune A from 2013 to 2023.

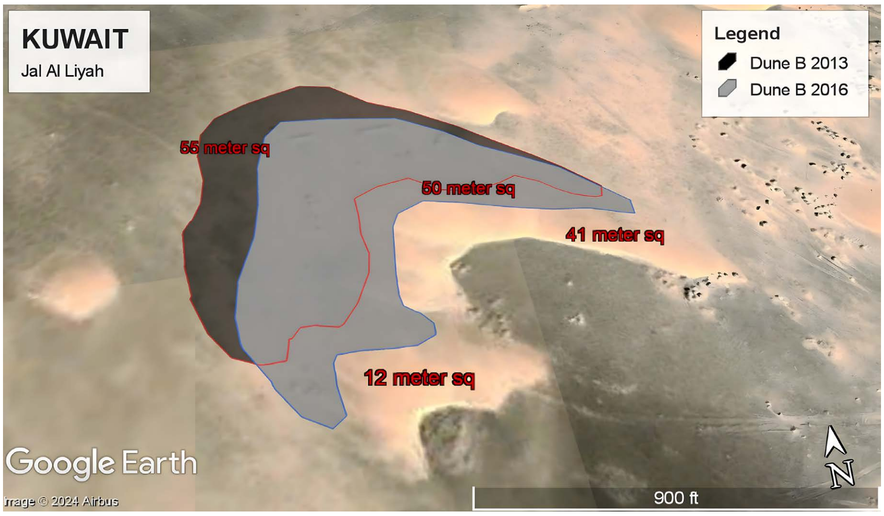

Figure 23. Morphological changes of Dune B from 2013 to 2023.

Abrasion losses and dune migration are important processes in arid zones, and they are attributed mainly to wind and sediment action. Analysis of migration rates showed migration rates ranging from 4 to 60 meters per year. The above-mentioned rates table from (3 to 8) shows the impact of wind strength, annual changes, and dune geometry on sand movement.

The occupation structure in the grid-based approach used in this study was simple to apply to analyze the migration level in the past three decades. With baselines introduced and displacement evaluated for subsequent years, the study provides a detailed view of dune dynamics. This methodology is most appropriate for Kuwait, where barchan-type dunes are well developed in a crescent shape and consistently migrate in the downwind direction. It provides insights into two major aspects of dune morphodynamics.

Table 5 shows the migration distances from 1993 to 2023 for each polyline, which represents the dune line in the analysis.

Table 5. Distances of migration between 1993 and 2023.

ID	Shape	Shifting Distance (Meter)
1	polyline	736.2
2	polyline	811.63
3	polyline	402.57
4	polyline	1426.7
5	polyline	955.96
6	polyline	889.44
Average migration		870.41 (29.01/yr)

Remote sensing has labeled hematite and ferric or aggregated iron oxides in Kuwait's desert. This standard paradigm is utilized in spectral analysis for mineral mapping in deserts worldwide.

Importantly, hematite has a particular spectral signature in the VNIR. As such, it has been the focus of prior research in deserts such as the Sahara, where the mineral gives its characteristic reddish color to the scenery [20]. This process is otherwise called oxidative weathering.

It is usually evident on rocks sampled in arid regions where preceding weathering factors like organic activities and drastic temperature changes are minimal. Likewise, ferric iron oxides, detectable using SWIR bands, are critical for determining the part played by iron-bearing minerals in determining the physical and chemical character of desert sands.

In Kuwait, tools such as QCC maps, ASTER imagery, and Fe^{3+}-based spectral analysis were used to map out these minerals accurately, information that played an important role in understanding the sedimentary processes of the region. Hematite and Ferri iron oxides are present in spatial locations representing aeolian activities and imply that they are derived from sediment transport from up-wind source areas or fluvial deposits from ancient rivers. These observations are consistent with other research in which hematite-rich sands are associated with paleoenvironmental conditions, such as the ancient river system in the Sahara Desert [24].

The incorporation of mineral analysis into dune dynamics is a new development. Unlike previous papers focusing solely on identifying minerals in a particular area and their distribution without regard to sand response, this study links mineral data to sand dynamics to predict dune stability and mobilization potential. For instance, a tight matrix from hematite-enriched sands may slow the migration rate, which is in agreement with other studies from the Arabian Peninsula. They argue that remote sensing is more advantageous for environmental management because it focuses on the distribution of minerals and what this means for the function.

The variation in dune migration rates observed in the Jal Al-Liyah region is influenced by a combination of factors, including dune morphology, wind exposure, grain size distribution, and mineral composition. Smaller barchan dunes, for example, tend to migrate faster than larger linear or star dunes due to their lower mass and simpler aerodynamic shape. From a mineralogical perspective, dunes dominated by high-purity quartz exhibit faster migration rates, as these grains are typically well-sorted, lighter, and less cohesive, making them more responsive to prevailing wind regimes. In contrast, dunes with higher concentrations of Fe^{3+} coatings or other heavy minerals may migrate more slowly due to increased grain density and surface crust formation, which stabilizes the dune surface.

Using Landsat and ASTER imagery places this work within the literature on remote sensing applications in desert landscapes. This is a key facet in managing the difficulties that stem from the geography of these areas, thereby fulfilling the promises offered by remote sensing.

Appreciation of spectral indices like NDSI, NDSDI, and NDESI confirms the efficiency of such tools in mapping dunes and detecting desertification. In addition, this research summarizes the existing knowledge on aeolian processes by exploring the rate and pattern of dune mobility in Kuwait. Unlike prior attempts at documenting Kuwait's dunes or addressing the issues of dune mobility and stability, where researchers confined themselves to particular areas or dune forms, this investigation encompasses a cross-section of Kuwait's dune fields during three decades. The migration rates captured and their spatial pattern afford practical information on infrastructure development and desertification. By combining mineral analysis with migration studies, this

Research also provides a fresh view of how geochemical attributes determine sand migration (**Figure 24**).

Previous research supports a compositional control on dune mobility. In the Rub' al Khali, Moufti (2013) [25] found that dunes with higher iron-oxide content (e.g., magnetite, ilmenite) exhibited greater surface crusting and reduced migration compared to pure quartz dunes. Similarly, in the northern Sahara, Hassani *et* *al.* (2019) [26] demonstrated that dunes with thicker hematite/goethite coatings—visible as reddish hues—were more stabilized, reflecting a geochemical crust effect. In contrast, quartz-rich dunes in the Sahara and Rub' al Khali (>95% quartz) are typically highly mobile. These findings align with the ASTER-derived indices showing that quartz-dominated zones in Jal Al-Liyah are among the most mobile, while iron-oxide–rich areas exhibit lower migration rates, providing a regionally corroborated, statistically supported framework for mineralogy-driven dune stability.

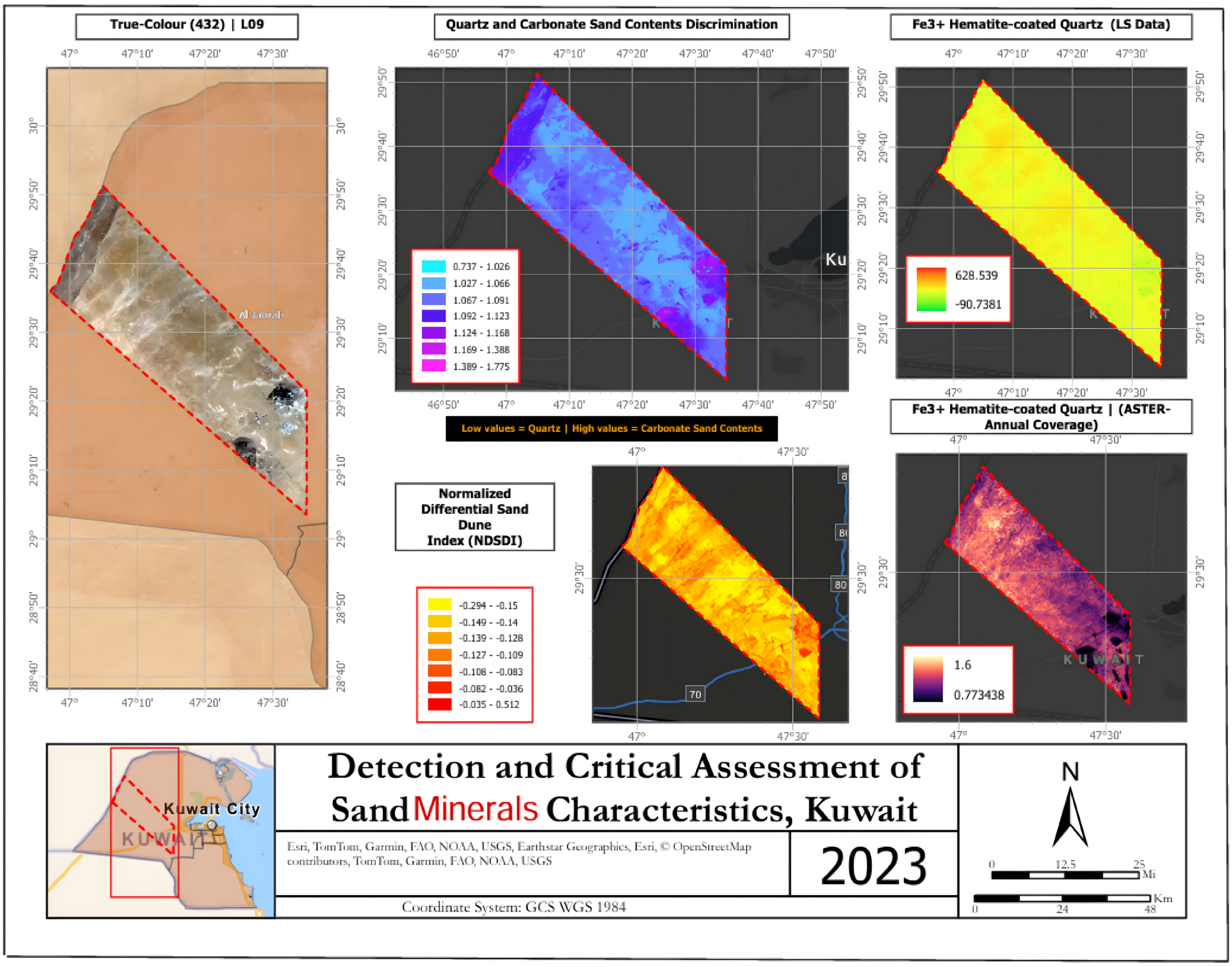

Figure 24. Sand mineral characteristics in 2023.

Sand minerals in the southern part of the Jal Al-Liyah area are composed of quartz, carbonate sands, iron-coated sands, and hematite-coated quartz sand.

- Referring to NDSDI in 2023: quartz and carbonate sand cover 45% of the study area.
- Referring to the Fe^{3+} coated quartz map in 2018: Fe^{3+} hematite-coated quartz covers 60% of the study area.
- Referring to the QCC map in 2023: quartz sand covers 40% of the study area.

- Referring to the ASTER map in 2023: Fe^{3+} hematite-coated quartz covers 50% of the study area.

This teaching and learning approach fits healthy international strategies to contain the environmental menace of desertification. The results also show that the aeolian process occurred everywhere, implying that the process of sand movement in Kuwait conforms to other deserts.

As in any research, several limitations could affect this study. A major area for improvement in the research is the limitation of data availability and the usage of Landsat and ASTER satellite data, which possess some disadvantages, such as spatial and temporal resolution.

Such limitations might hold back the accuracy and scope of the analysis. Moreover, variations in the physical characteristics of the environment, such as wind range, precipitation, and other factors, can lead to variability in the movement of sands and hence complicate the analyses being conducted. This research faces several limitations, including the limitation of the study area, which is only focused on Kuwait. These geographical boundaries may limit the application of the findings to other areas within arid environments with unique geophysical and climatic characteristics.

The study also attempts to state the delimitations of the work to establish its boundaries. It mainly focuses on using a remote sensing approach, especially imagery, to survey and measure dunes and does not consider ground observation. Ensuring this focus makes operations efficient, but it can fail to collect some specific micro-level trends obtainable only through on-site surveys. Moreover, the research focuses on a specific temporal density, which allows for a manageable approach to examining the occurrence of sand displacement over time.

Lastly, the study adopts special spectral indices ideal for the arid environment: NDSDI, NDESI, and NSI. Several indices, less important for distinguishing the sand regions, have not yet been used to prevent the analysis outcome from becoming diluted or lost.

5. Conclusions

The study aimed to establish whether the spectral indices, especially the NDSDI and the NDESI, could capture and quantify dunes in the Kuwait desert landscape. It also identified the extent to which dunes move and factors attributed to the shift, including wind effects, human interference, and climatic factors. Further, the study sought to develop a correlation between the types of deposits and the stability of mass movement of dunes by considering the variation of minerals in the area, particularly concerning hematite and iron oxides ferric. Lastly, it offers a chance to evaluate the prospects of employing highly developed remote sensing approaches to solve some problems related to dunes for environmental appreciation and planning management. Spectral indices were proven effective, several migrations are described for different reasons, and a relationship between mineral compositions and dune stability is shown.

This study also indicated that remote sensing technologies can serve as sufficient inputs to replace the depleted environment in Kuwait's deserts.

Future studies of dune dynamics in Kuwait include using satellites with high spatial resolution, such as Sentinel-2 or hyperspectral sensors, to improve mineral map results and migration analysis. Some automation techniques that could boost the scale and accuracy of migration measurements are the Co-registration of Optically Sensed Images and Correlation (COSI-Corr).

Additional research comparing the study area with other deserts, such as the Sahara or Arabian deserts, will further enrich the study by comparing the results with those of other regions experiencing the desertification process. Field-based sediment sampling or wind measurements further support and enhance the study.

Acknowledgements

The authors greatly appreciate the GIS Lab in the Geography Department at Kuwait University for providing ArcMap 10.8.2 and other program licenses that facilitated this research. Additionally, sincere appreciation is extended to Eng. Bader Matar for his invaluable support and technical assistance during this work.

Authors' Contributions

Dr. Adeeba Al-Hurban provided and developed the intellectual, comprehensive geological and sedimentological background of the study site and its geomorphology, and encouraged Ibrahim Mohammed to investigate the characteristics, evolution, and development of the sand dune field in the south of Al-Liyah during different time periods in terms of migration, mineralogy, and sedimentology. Ibrahim Mohammed developed the theoretical aspect of sand dune detection and designed the remote sensing and GIS-extracted maps, then presented the computational framework to Dr. Adeeba Al-Hurban for discussion. Ibrahim Mohammed analyzed and interpreted the data. Both authors contributed to the final version of the manuscript by revising it critically. Both authors are accountable for all aspects of this work and approve the publication of the version.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Corrie, R.K., Ninomiya, Y. and Aitchison, J.C. (2010) Applying Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Spectral Indices for Geological Mapping and Mineral Identification on the Tibetan Plateau. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Science*, **38**, 464-469.

[2] McCauley, J.F., Schaber, G.G., Breed, C.S., Grolier, M.J., Haynes, C.V., Issawi, B., *et al*. (1982) Subsurface Valleys and Geoarcheology of the Eastern Sahara Revealed by Shuttle Radar. *Science*, **218**, 1004-1020.
https://doi.org/10.1126/science.218.4576.1004

[3] Lancaster, N. (1989) Star Dunes. *Progress in Physical Geography: Earth and Environment*, **13**, 67-91. https://doi.org/10.1177/030913338901300105

[4] Abd El Aal, A.K., GabAllah, H.M., Megahed, H.A., Selim, M.K., Hegab, M.A., Fadl, M.E., *et al.* (2024) Geo-Environmental Risk Assessment of Sand Dunes Encroachment Hazards in Arid Lands Using Machine Learning Techniques. *Sustainability*, **16**, Article 11139. https://doi.org/10.3390/su162411139

[5] Al-Helal, A.B. and Al-Awadhi, J.M. (2005) Assessment of Sand Encroachment in Kuwait Using GIS. *Environmental Geology*, **49**, 960-967. https://doi.org/10.1007/s00254-005-0134-8

[6] El-Aal, A.E.K.A., Al-Awadhi, J.M. and Al-Dousari, A. (2022) The Geology of Kuwait (Regional Geology Reviews).

[7] https://www.windy.com/29.362/47.954?satellite,29.146,47.784,9

[8] Al-Hurban, A.E. and Al-Ostad, A.N. (2010) Textural Characteristics of Dust Fallout and Potential Effect on Public Health in Kuwait City and Suburbs. *Environmental Earth Sciences*, **60**, 169-181. https://doi.org/10.1007/s12665-009-0177-3

[9] Al-Dousari, A. and Pye, K. (2005) Mapping and Monitoring of Dunes in Northwestern Kuwait. *Kuwait Journal of Science & Engineering*, **32**, 119-134.

[10] Bagnold, R.A. (1973) The Effect of Sand Movement on the Surface Wind. In: *The Physics of Blown Sand and Desert Dunes*, Springer, 57-76. https://doi.org/10.1007/978-94-009-5682-7_5

[11] Bruno, L., Horvat, M. and Raffaele, L. (2018) Windblown Sand along Railway Infrastructures: A Review of Challenges and Mitigation Measures. *Journal of Wind Engineering and Industrial Aerodynamics*, **177**, 340-365. https://doi.org/10.1016/j.jweia.2018.04.021

[12] Howari, F.M., Baghdady, A. and Goodell, P.C. (2007) Mineralogical and Gemorphological Characterization of Sand Dunes in the Eastern Part of United Arab Emirates Using Orbital Remote Sensing Integrated with Field Investigations. *Geomorphology*, **83**, 67-81. https://doi.org/10.1016/j.geomorph.2006.06.015

[13] Dorabad, F.H., Mashhadi, N. and Keshtkar, A. (2024) Morphology, Mobility and Grain Size Characteristics in New Sand Dunes (Case Study: Young Erg of Abshirin). *Physical Geography Research*, **55**, 123-145.

[14] Muhs, D.R. (2004) Mineralogical Maturity in Dunefields of North America, Africa and Australia. *Geomorphology*, **59**, 247-269. https://doi.org/10.1016/j.geomorph.2003.07.020

[15] https://en.wikipedia.org/wiki/Great_Sand_Dunes_National_Park_and_Preserve

[16] Hesp, P., Martinez, M., da Silva, G.M., Rodríguez-Revelo, N., Gutierrez, E., Humanes, A., *et al.* (2010) Transgressive Dunefield Landforms and Vegetation Associations, Doña Juana, Veracruz, Mexico. *Earth Surface Processes and Landforms*, **36**, 285-295. https://doi.org/10.1002/esp.2035

[17] Nguyen, D., Hilton, M. and Wakes, S. (2022) Wind Flow Dynamics and Sand Deposition behind Excavated Foredune Notches on Developed Coasts. *Earth Surface Processes and Landforms*, **47**, 1698-1719. https://doi.org/10.1002/esp.5341

[18] Hugenholtz, C.H., Levin, N., Barchyn, T.E. and Baddock, M.C. (2011) Remote Sensing and Spatial Analysis of Aeolian Sand Dunes: A Review and Outlook. *Earth-Science Reviews*, **111**, 319-334. https://doi.org/10.1016/j.earscirev.2011.11.006

[19] Al-Dabi, H., Koch, M., Al-Sarawi, M. and El-Baz, F. (1996) Evolution of Sand Dune Patterns in Space and Time in North-Western Kuwait Using Landsat Images. *Journal of Arid Environments*, **36**, 15-24. https://doi.org/10.1006/jare.1996.0230

[20] Al-Dousari, A.M., Al-Sahli, M., Al-Awadhi, J., Al-Enezi, A.K., Al-Dousari, N. and Ahmed, M. (2023) Sand Dunes in Kuwait, Morphometric and Chemical Characteristics. In: El-Aal, A.E.K.A., Al-Awadhi, J.M. and Al-Dousari, A., Eds., *The Geology of Kuwait* (*Regional Geology Reviews*), Springer, 51-81.

[21] Ghoneim, E. and El-Baz, F. (2007) The Application of Radar Topographic Data to Mapping of a Mega-Paleodrainage in the Eastern Sahara. *Journal of Arid Environments*, **69**, 658-675. https://doi.org/10.1016/j.jaridenv.2006.11.018

[22] Khalaf, F.I. and Ala, M. (1980) Mineralogy of the Recent Intertidal Muddy Sediments of Kuwait—Arabian Gulf. *Marine Geology*, **35**, 331-342. https://doi.org/10.1016/0025-3227(80)90124-3

[23] Al-Dousari, A.M., Misak, R. and Shahid, S. (1988) Soil Compaction and Sealing in Al-Salmi Area Western Kuwait. *Land Degradation & Development*, **11**, 401-418.

[24] Vermeesch, P. and Drake, N. (2008) Remotely Sensed Dune Celerity and Sand Flux Measurements of the World's Fastest Barchans (Bodélé, Chad). *Geophysical Research Letters*, **35**, L24404. https://doi.org/10.1029/2008gl035921

[25] Moufti, A.M.B. (2013) Mineralogy, Geochemistry and Possible Provenance of Desert Sand Dunes from Western Rub' Al Khali Area, Southeastern Saudi Arabia. *International Journal of Basic and Applied Sciences*, **2**, 399-407. https://doi.org/10.14419/ijbas.v2i4.1292

[26] Hassani, M., Saadoud, D., Chabou, M.C., Martín-Peinado, F.J. and Sánchez-Marañón, M. (2019) Spectral Signs of Aeolian Activity around a Sand-Dune Belt in Northern Algeria. *Catena*, **182**, Article 104175. https://doi.org/10.1016/j.catena.2019.104175