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Comparison Study on Sedimentomorphological Characteristics Using Integrated Geo-Techniques: A Case Study of Two Representative Areas in Kuwait

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Abstract

Intensive aeolian processes occur due to the scarcity of rainfall and lack of vegetation cover in arid regions. The study of recent surface sediments in arid areas is important for environmental assessments, evaluation of natural resources, and land use planning. In this study, two areas were chosen as they show changes in lithology, environment and landforms. The two study areas are Al-Rawdatain in the northern part, and Al-Managish in the southern part of Kuwait. The current study aims to define the sedimentomorphic zones in these areas, with an emphasis on Quaternary geomorphological evolution by providing an integrated approach based on satellite images, topographic maps, field measurements, and laboratory analysis. Remote sensing data were spatially analyzed to classify and detect the temporal changes in the surface sediments and geomorphology based on the field measurements (n = 42) as ground truthing points for supervising the classification. Samples from both areas were collected and subjected to grain size (dry mechanical sieving) and X-Ray Diffraction (XRD) analysis. The resulting data were statistically analyzed for grain size distributions and mineralogy based on the US standard set of sieves. The study found that the Aeolian sand sheet deposits are the most frequent recent surface deposits in Kuwait and cover most of the other sediments. The direction of movement of the sand sheets is from NW towards SE. The mineralogical composition of the aeolian recent surface sediments revealed that they are mostly derived from the Dibdibba Formation and Tigris-Euphrates fluvial terrace deposits. Quartz is the most frequent component of the studied surface sediments in the study areas (66%). The calcite mineral is also found in subordinate amounts in the study areas (10%).

Keywords

Desert Geomorphology, GIS, Remote Sensing, Al-Rawdhatain, Al-Managish, Land Use, XRD

1. Introduction

Geomorphological studies have increased our ability to solve natural problems, including understanding the evolution of surface forms, hazard prediction, spatial planning, risk management, and other applications [1]. Traditionally, geographers and geologists have studied surface features through field surveys [2] [3]. This method is very effective for the accurate mapping of specific locations, but it is costly in terms of time and economy [4] [5]. The development of remote sensing (RS) sciences and geographic information systems (GIS) have contributed to the provision of huge spatial data on the surface of the Earth, with the ability to analyze this data in a specific spatial framework. With this, it is possible to extract and classify many of the phenomena of the surface through satellite images and aerial photography through the relationship and disparity of electromagnetic radiations reflected and emitted by different surface features [6]. Remote sensing data also allows us to monitor the temporal developments that occur through various phenomena through the huge archive that dates back to the 1980s, when space imaging began.

Spatial techniques including spatial and aerial image processing, geographic information systems, and global positioning systems have provided geomorphologists with the ability to solve complex and intertwined problems among the various fields [7]. This includes re-examining traditional concepts and problems and assisting in the emergence of new ones [8], the development of algorithms and the spatial analysis of various phenomena [9], however, the investigation of the accuracy of results based on remote sensing data and spatial technology solutions are an important requirement for future research.

Although spatial techniques provide solutions, they cannot replace field surveys. Several studies have used statistical methods to investigate the accuracy of studies based on spatial techniques, where field data are compared with remote sensing data through correlation coefficients to determine the accuracy of the extracted spatial models [10] [11]. For example, [12] extracted data related to the topography of the land and the network of valleys, and arranged them using spatial techniques, in order to analyse their relationship to the risks related to flash floods in desert areas. Also, many other studies have relied on field data as a reference basis for classifying Earth's surface phenomena using remote sensing data and spatial models (supervised classification, [13]). Moreover, field data have been used in many studies to geometrically correct models, especially those extracted from aerial photography [3] [14].

The current study aims to define the sedimentomorphic zones (*i.e.*, sedimentological and geomorphological zones) in two representative areas in Kuwait (Al-Rawdatain in the northern part, and Al-Managish to the south) that show changes in lithology, environment and landforms, with an emphasis on Quaternary geomorphological evolution and deposits by providing an integrated approach based on satellite images, topographic maps, field measurements, and laboratory analysis. These two areas provide good examples showing how the environments, surface landforms, surface sedimentology and geomorphology, as well as the impact of the anthropogenic activities and land use forms affected and changed the surface geomorphology in the northern sector of Kuwait (represented by Al-Rawdhatain area) and in the southern sector of Kuwait (represented by Al-Managish area), as they are of different locations towards the prevailing sediments and sand feed transport direction, where the former is at the up-direction and the latter is at the down direction.

Before utilization of desert sites for any development activity, it is of great importance to understand the main geomorphic processes that are acting on the area. Most of the previous studies have not dealt with the comprehensive assessment of the sedimentomorphic aspects of the selected study areas. Therefore, it is necessary to establish basic information about the geomorphologic and sedimentologic characteristics of the areas of different significance and location such as the two study areas for the establishment of a detailed database for future selection of recreational areas or planning socio-economic development and industrial activities. Hence, this research study was designed to conduct a detailed geomorphic and sedimentologic assessment of these representative areas with an emphasis on the geomorphic processes and changes.

Moreover, the study can be used for assessing socioeconomic impact on the sedimetomorphological inputs of the studied areas. If no attention was paid to desert processes, this might adversely impact the resources and reservoirs in both areas (fresh and brackish water as well as oil resources and reservoirs) and their users. Utilization of geomorphic zones requires a comprehensive understanding of all existing procedures.

2. Previous Studies in Kuwait

2.1. Aeolian Processes & Landforms

The desert surface of Kuwait is mostly covered by loose mobile sediments that are continually transported along the surface under the influence of the wind. The aeolian processes (including deflation, transportation and deposition) in Kuwait are very active and are related to the location of Kuwait, the scant and irregular rainfall, the hot and dry season [15]. Deflation processes are evident in Kuwait by the abundant occurrence of several types of lag deposits, erosion of exposed bedrock (yardangs) and deflation hollow [15]. In Kuwait, desert lag covers most of the northern part of the country [16].

Aeolian deposits are the most frequent type of surface sediments in Kuwait. Residual deposits in Kuwait are of two types, namely residual gravel deposits and duricrusts [17]. Playa deposits in Kuwait generally consist of mud that is covered partially with aeolian deposits. Desert plain deposits originate through the combined effect of water and wind. Four types of Aeolian deposits were recognized: sand sheets, sand dunes, sand drifts, and aeolian wadi fill [18] [19]. Kuwait is influenced by two sand belts entering the country from Iraq, the larger through Al-Huwaimliyah, and the other through Al-Qashaniya [20] [21]. Sand sheets prevail mostly in the southern part of the country as well as in the vast northern area of Kuwait. [18] define three types of sand sheets, namely: smooth sand sheet, rugged vegetated sand sheet and active sand sheet. Aeolian wadi fill deposits mostly prevail in the northeastern corner of Kuwait.

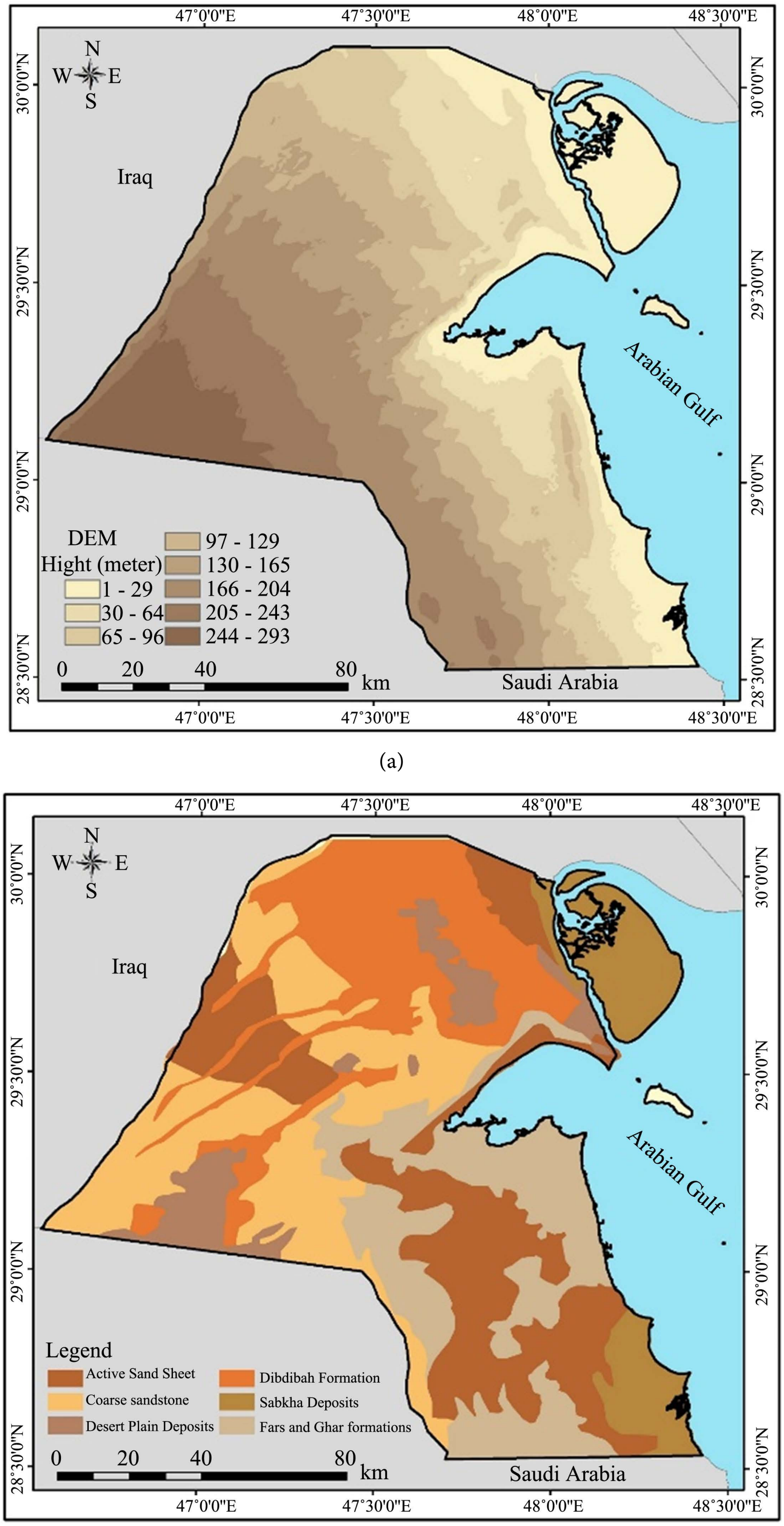
Subsurface data acquired from oil drilling reaching a depth of 6000 meters has outlined a succession of sediments ranging in age from Pleistocene to Triassic [22]. The surface rocks throughout the State of Kuwait consist of sediments ranging in age from the middle Eocene to Quaternary [23]. Quaternary surficial sediments include Pleistocene gravel and sand, and Holocene sediments include marine sand, coastal deposits, beach rocks, sabkha deposits, desert floor deposits, alluvium and aeolian sands.

The recent surface deposits of Kuwait are considered to be derived from local sources [15]. The low-lying flat coastal area forms a continuous belt along the entire coast of Kuwait and varies considerably in shape and width. The geomorphic differences reflect variations in the sedimentary environments. In general, the coastal area can be subdivided into northern and southern areas [24] [25] [26]. The northern region is more closely related to the Mesopotamian Plain; the southern region reflects features of the Arabian stable foreland unit that is composed of oolitic sand, sandstone and limestone with some flat sabkhas [27] [28] [29]. Recent field investigations, aerial photographs and Landsat images indicate progressive expansion of active sand sheets [30] [31].

For sedimentomorphic mapping, several papers were published. [32] produced a map for Kuwait, which identified the local potential source areas of the dust storm sediments. The map was later validated by [33], who produced a sedimentomorphic map of Kuwait from satellite imagery. Another study was conducted by [21], which investigate and delineate the mobile sand sediments in six areas in Kuwait. [34] updated the surface sediment maps prepared by [21]. [18] classified the recent surface sediments in Kuwait into six major groups. With the increase of aeolian processes in the 1980s, the desert surface of Kuwait was mostly covered by mobile aeolian sediments [35] [36] [37]. During this period, several studies were conducted on aeolian processes and aeolian landforms [38] [39] [40] (**Figure 1(a)** and **Figure 1(b)**).

2.2. Geomorphic and Morphostructural Features & Surface Geology

Geological structure and lithology also control the morphology of the country.



(a)

(b)

Figure 1. (a) Topographic map of Kuwait [42], (b) Geological map of Kuwait [42].

Kuwait Institute for Scientific Research [41] divided the morphology of Kuwait into 15 geomorphic zones. [38] classified the surface features of Kuwait into different geomorphic zones according to morphostructural features. The geomorphic zones originated during the late Tertiary-Quaternary periods as a result of tectonic, erosional or depositional processes, or their combination [38].

The morphostructure in Kuwait reflects the subsurface configuration, such as the depressions that are due to tilting, and the inter-ridge linear depressions that were formed due to subsequent fluvial erosion [16]. Previous attempts were made to develop surface geological maps of Kuwait. [23] produced a geological map of Kuwait at a scale of 1:250,000 to show the distributions of the different geological sediments. The Kuwait Oil Company [43] developed a geological map of Kuwait that displays recent coastal and desert deposits. In the sedimentomorphic map of [32], a detailed classification of recent surficial deposits is given. In smaller areas, [34] studied the surface sediments of some selected sites in Kuwait. The geomorphic zones of Kuwait outlined by Kuwait Institution for Scientific Research [41] are delineated to show the impact of geomorphology on the economic and geological aspects. The distribution of recent surface sediments and landforms in the northern and southern part of Kuwait is given by [19] (**Figure 2**). An atlas of Kuwait from satellite images produced by [42] shows the physiographic characteristics of Kuwait (**Figure 3(a)**).

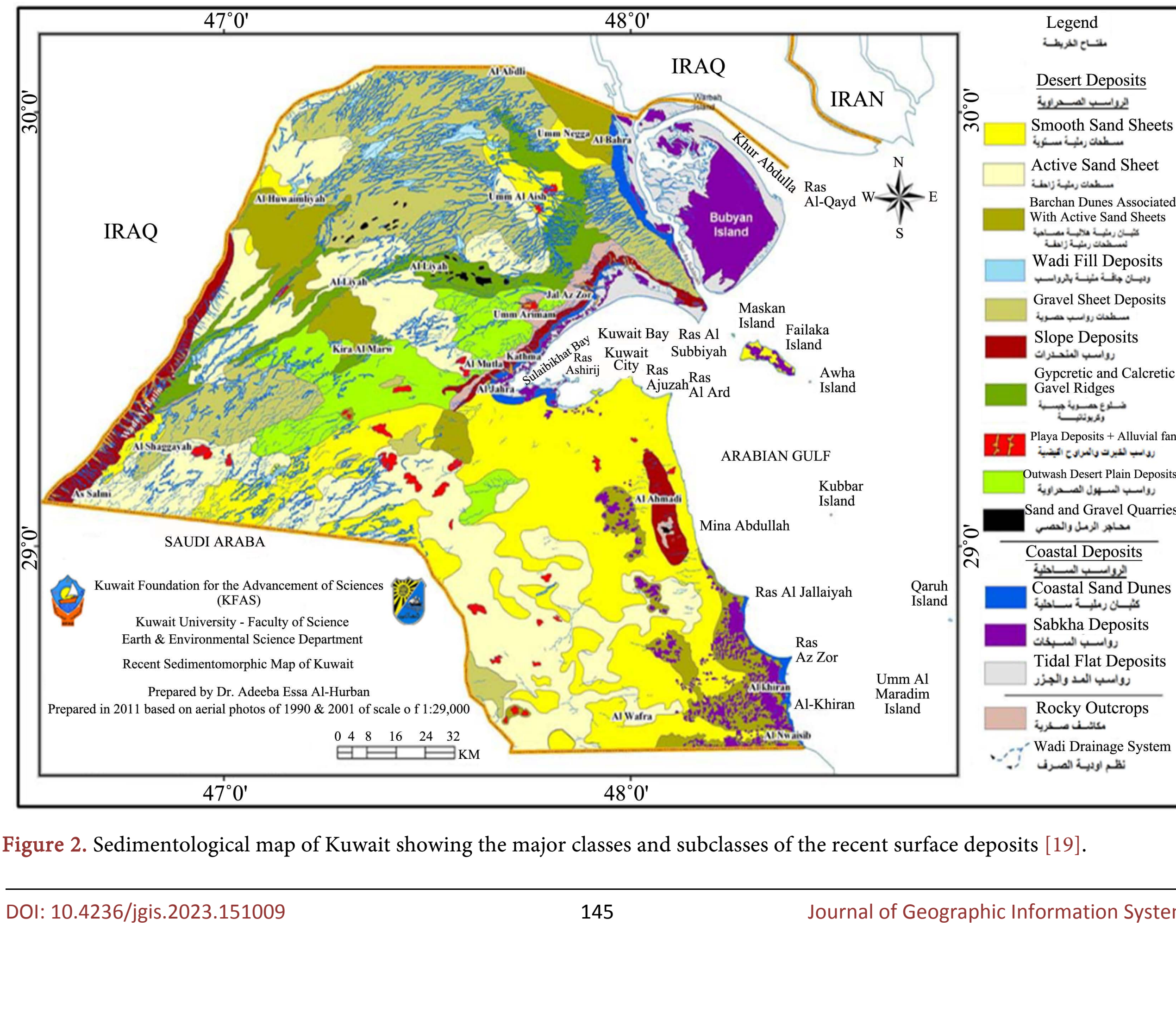
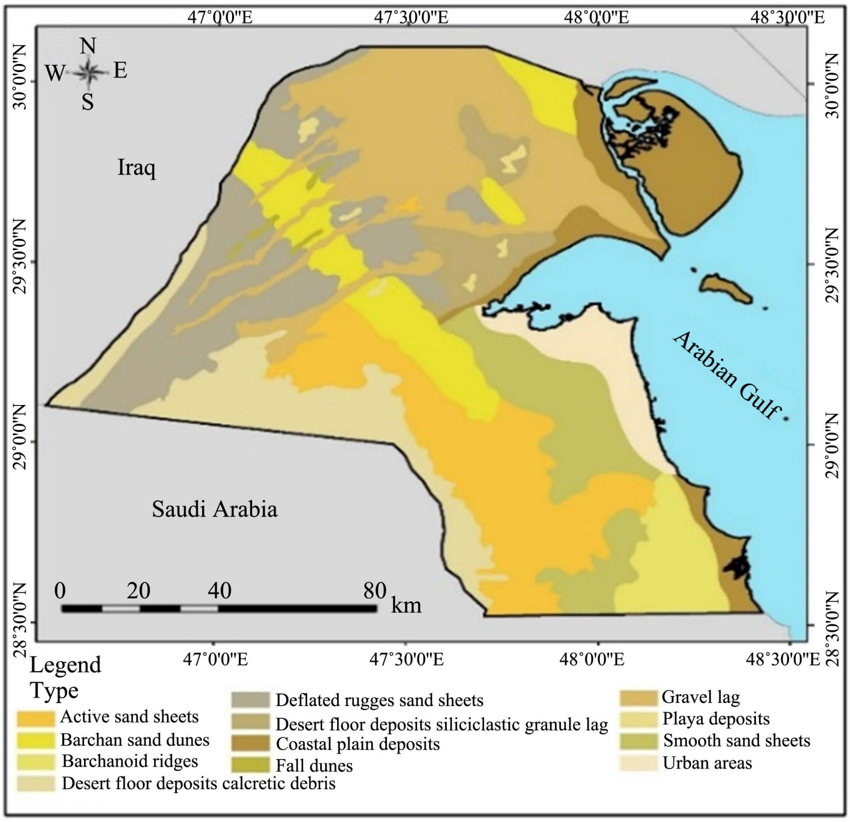


Figure 2. Sedimentological map of Kuwait showing the major classes and subclasses of the recent surface deposits [19].



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Fall dunes
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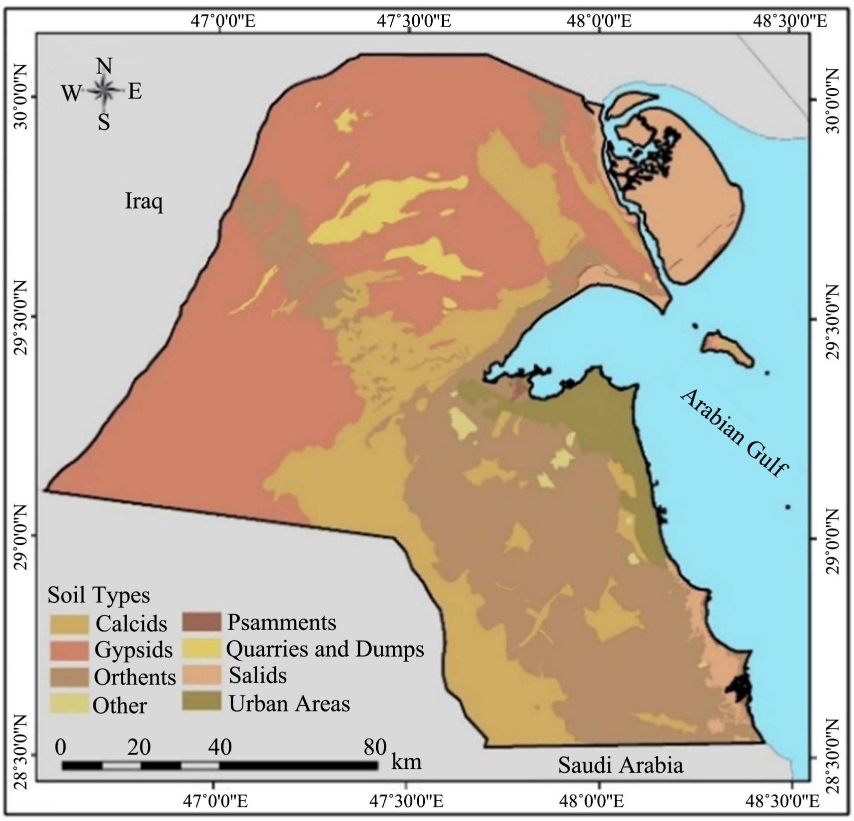
Smooth sand sheets
Urban areas

(a)



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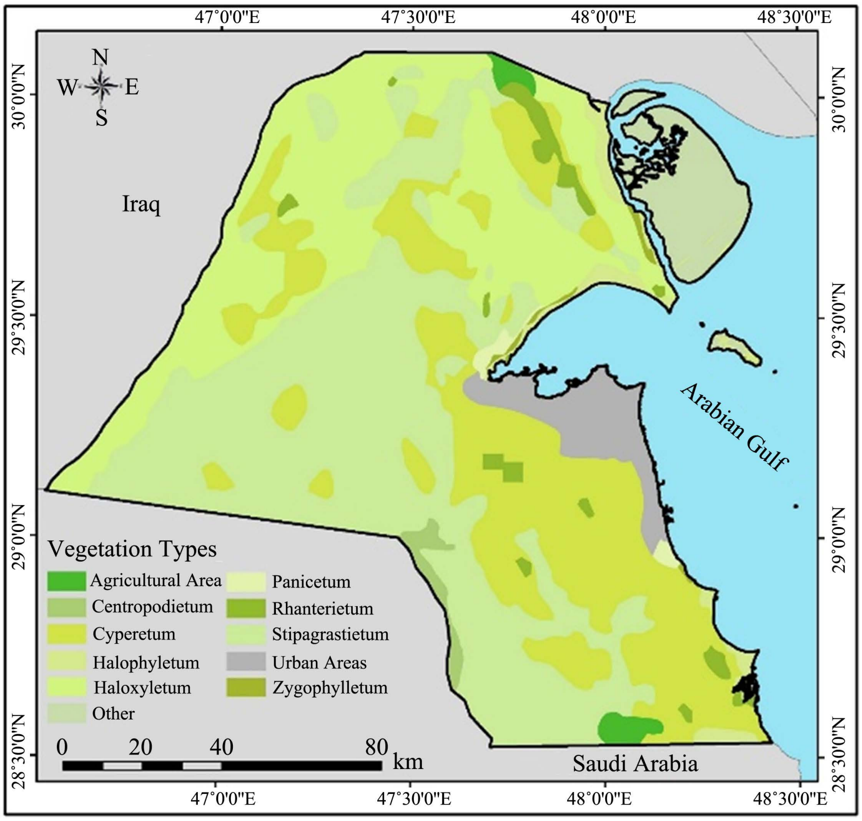


(c)

Figure 3. (a) Geomorphological map of Kuwait [42], (b) Soil map of Kuwait [42], (c) Vegetation map showing different plant communities in Kuwait [49].

2.3. Soil & Vegetation

[44] surveyed the soils of Kuwait on a reconnaissance basis. Briefly, four main soil groups have been recognized: desert soils; desert-regosol intergrade soils; lithosols; and alluvial soils. Soils of Kuwait are calcareous. The duststorms and dustfalls contribute a considerable amount of calcareous dust to the soils [45]. Recently, [46] conducted a detailed soil survey for the State of Kuwait and came out with a soil map of Kuwait (**Figure 3(b)**).

Sand and changes in surface roughness are over large areas [47] [48]. In addition, vegetation can grow through accumulating sand sheets. [49] prepared a recent vegetation map showing different plant communities in Kuwait (**Figure 3(c)**).

2.4. Climate

The climate of the state of Kuwait is characterized by a long, hot, dry summer and a short, warm and occasionally rainy winter, as a result of Kuwait's location in the desert region which is of continental climate [10] [50]. Usually, dusty winds blow during summer months and the humidity percentage increases, where the maximum temperature was recorded as 51˚C in July 1978, whereas the minimum temperature was −4˚C in January 1964. The mean temperature ranges between 47˚C in summer and 6˚C in winter (The Directorate General of

Civil Aviation). This great fluctuation in temperature is associated with many differences in the annual averages of precipitation which ranges from 22 mm to 352 mm annually. The fluctuation in the amount of rainfall is considered one the most important natural factors causing the environmental deterioration in the state of Kuwait, where such a fluctuation. Moreover, the sand sheets covering the surface of Kuwait help increase the temperature, where they are bad heat conductors and consequently the solar radiation falling on the surface of the sand spreads only through the surficial layer.

Winds are regarded as the most important factor affecting the sand movement in the area. The northerly and north-westerly winds, which are the predominating wind direction in Kuwait, blow most of the year [50] [51] (**Figure 4**). Winds blow more during the summer months and their speeds may reach 120 km/h; they are very hot and dry and they are locally named *Al-Sumoom*. They blow from the Saudi, Iraqi and Syrian deserts and accompany the intensive drought which occurs in during the summer months, in which the land surface lacks the vegetation cover and the soil is loose and unconsolidated. Therefore, the action and speed of the winds lead to the occurrence of sandstorms, locally known as *Al-Touz*. The creeping sand over the natural vegetation in the state of Kuwait forms a geomorphological phenomenon known as nabkhas.

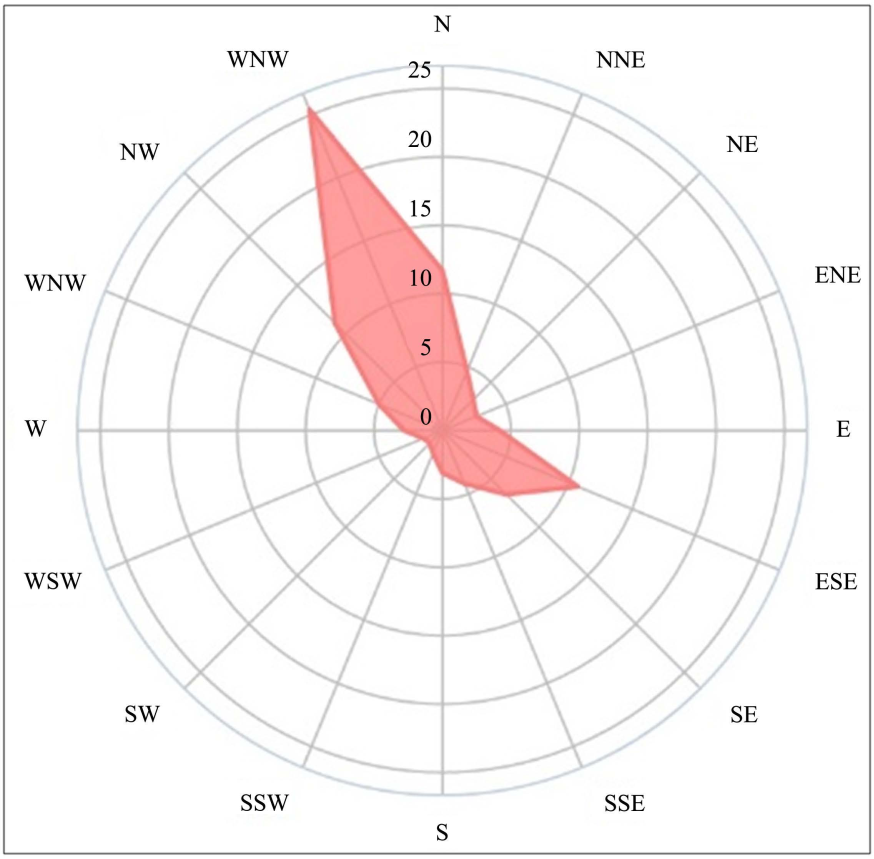


Figure 4. Wind direction in the state of Kuwait during the period from September 2006 to September 2016 (windfinder.com).

2.5. Remote Sensing & GIS

Remote sensing was widely used in the classification and detection of changes in the surface sediment geomorphology of Kuwait [52]. This is due to the availability and inexpensiveness of satellite remote sensing data. [33] used Landsat images to show the types and distribution of recent surface deposits of Kuwait on a sedimentomorphic map. A comprehensive study was conducted by [53] where the main objective of study was to identify, assess and map land degradation forms in the Mutlaa, Sulaibiyah, Ras Al-Subiyah and Al-Ahmadi-Al-Daher areas. Based on the results of field assessment and remote sensing information, land degradation status maps were prepared for study areas. In their project, [54] aimed to assess the environmental damage caused by the Iraqi invasion to the desert surface and coastal zone of Kuwait by remote sensing techniques. The project was carried out jointly by the Kuwait Institute for Scientific Research and Boston University (Center for Remote Sensing). The main objectives of the joint project were inventory of changes and assessment and mapping of surface changes and damage using field data and post-invasion Landsat TM digital data and aerial photographs. Studies by [52] [55] [56] used different image data consisting of countrywide coverage by Radarsat, ERS, IRS, and TM, to assess the desert environment and for land use mapping of some selected areas in Kuwait. Albanai used geographic information system and remote sensing to evaluate Failaka Island variability to sea level rise [10] [57], to map the morphology of Kuwait territorial waters [11], and to classify the spatial distribution of coastal geomorphological features in Kuwait [6] [13].

3. Material & Methods

3.1. Field Work and Laboratory Analysis

Geomorphological and sedimentological analysis were performed simultaneously to ensure optimal use of time and effort and to establish uniformity of data so that possible interrelationships between the physical parameters could be accurately defined. Detailed field sampling and investigation have been done for the selected areas. Due to some political obstacles and security measures, parts of the study areas were inaccessible. A total of 42 soil samples of known geographic coordinates using Global Positioning System (GPS) were collected (15 and 27 soil samples from Al-Rawdhatain and Al-Managish, respectively) from different depositional environments. At each location, the surface sediments (3 cm thick) that cover 40 cm^2 area were collected to get the most recently deposited sedimentation unit (**Figure 5**) according to the changes in types of sediments. The fieldwork was conducted to validate the geomorphic features delineated from satellite images, and geologic and topographic maps. Field descriptions of geomorphological and sedimentological features such as ridges and depressions were done.

To investigate the grain size distribution of sediments, characteristic size parameters were found and their possible geological significance was assessed

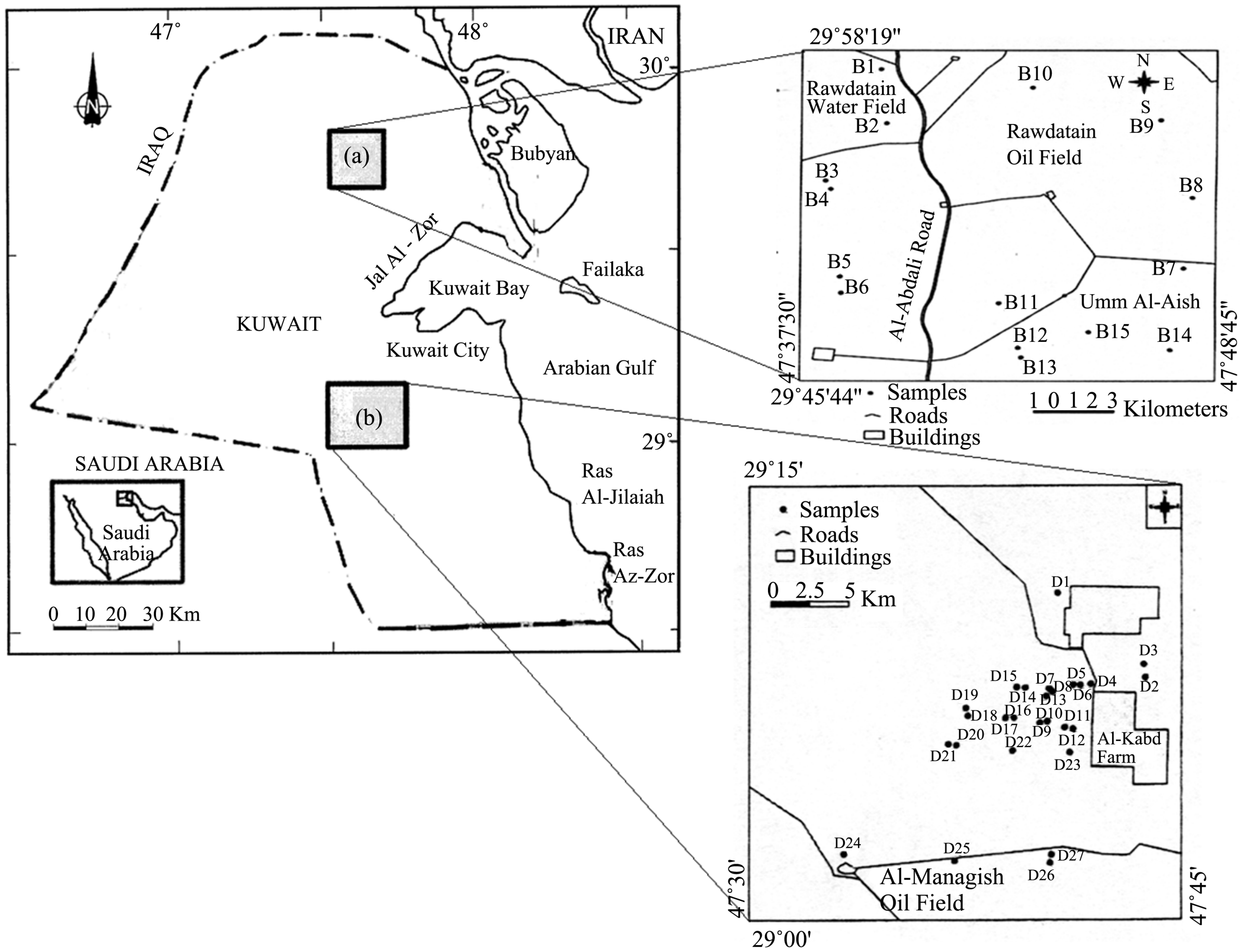


Figure 5. Location and sampling maps of the study areas. Study areas: (a) Al-Rawdhatain (Long. 47˚37'30" to 47˚48'45"E - Lat. 29˚45'44" to 29˚58'19"N); (b) Al-Managish (long. 47˚30' to 47˚45'E- Lat. 29˚00' to 29˚15'N).

using mechanical analysis by the US standard set of sieving [58] [59]. The data was then graphically represented by histograms and cumulative frequency curves for the identification of the various textural size parameters (mode, median, mean, sorting, skewness and kurtosis). Based on these graphical representations and certain statistical measure units, the characteristics of grain size distribution, size parameters and the interrelations of the size parameters of the collected samples were studied. Additionally, to understand the genesis and determine the potential sources of the sediments and to identify the minerals in these surface sediments, an X-ray diffraction analysis was done for mineral identification of the recent surface sediments in the study area. Some representative samples were selected for the qualitative-quantitative examination by a Siemens D.500 X-Ray Diffractometer instrument.

3.2. Spatial Analysis of Remote Sensing Data

Remote sensing data is extremely useful, particularly in desert terrain, to extract surface features on the land due to the lack of thick vegetation cover. Image enhancement techniques are available to selectively identify surficial material characteristics and geomorphic patterns [60]. These techniques include a multitude of filtering methods, principal component and classification analyses, and band-rationing. In our study, sedimentomorphic features were mapped using visual and digital methods. The process of selecting appropriate remote sensing data is inherent with the issue of a trade-off between spectral and spatial resolutions. A wide variety of different spectral and spatial sensors properties were used. These include Landsat satellites (1995 and 2010), IRS-1D (Indian Remote Sensing) in 2000, and ASTER for digital elevation data. They were selected together for consideration, keeping in view the terrain in Kuwait and the objective of the study. IRS data in raw format for Kuwait images were obtained for the study areas. The thematic data collected were digitized and analyzed to derive associative characteristics of the sedimentomorphic variables. Geomatica FOCUS (9.0) and ESRI's ArcGIS were selected for image processing and spatial modeling.

On the other side, topographic maps (1:100,000, 1:50,000 and 1:25,000) and SRTM digital elevation model of the two selected study areas have been used and analyzed using ArcMap 10.4.1 and watershed modelling system (WMS) to produce the related features maps. The different landforms in the area were delineated and classified and, with the help of field investigation and sample description, final sedimentomorphic maps were prepared for the study areas.

4. Results and Discussion

4.1. Al-Rawdhatain

Al-Rawdhatain covers about one-third of the northern part of the northern province of Kuwait. It is covered by clay layers from floods in earlier decades, as the area is a large catchment basin. Hydrogeological surveys revealed the presence of a high amount of usable groundwater in lenses. Topographically, the area slopes 5 - 7 degrees per kilometer from the north towards the south. The area is bounded by Jal Al-Zor escarpment to the east and the ridges of the basin and range area to the west [61]. The area contains a large number of freshwater wells; production from Pleistocene pluvial deposits reaches one-half million imperial gallons. **Figure 6** illustrates the topographic, sedimentomorphic and elevation maps of the study area. Comparing the sedimentomorphic map with the other maps of previous studies, it is found that the desert plain covers most of the area that used to be rugged sand sheet and gravel deposits, but the drainage system is from east to west. The playa in the southern corner of the area became elongated in shape due to erosional activity. A total of 15 samples were collected from the surface sediments covering the area and subjected to mechanical analysis (**Figure 7** and **Figure 8**). Some of these samples were analyzed by X-ray diffraction to determine the mineral constituents of sediments in the area. **Figure 9** shows X-ray diffraction results for one of the most common sediment types in the area.

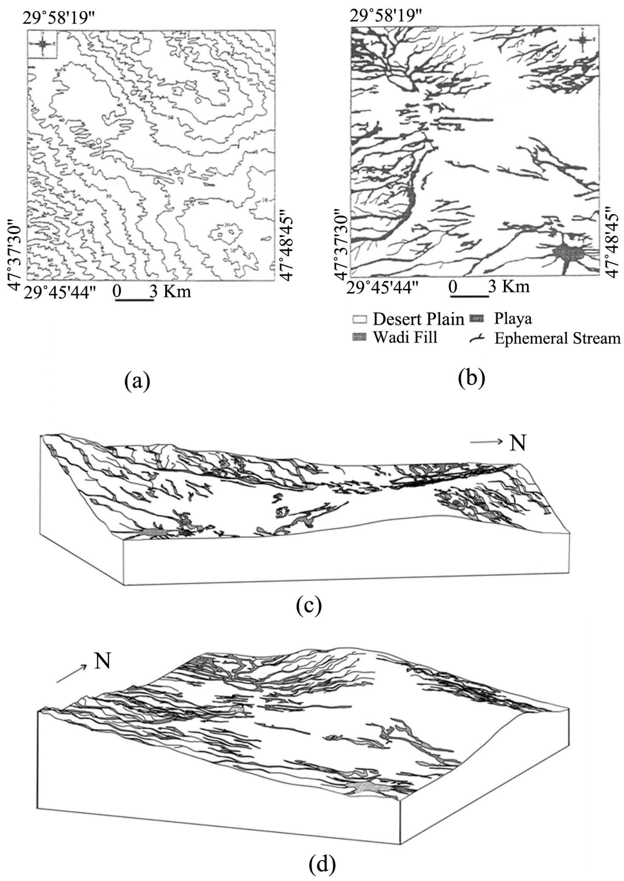


Figure 6. Different types of maps of Al-Rawdhatain area: (a) Topographic map, (b) Sedimentomorphic map, (c) and (d) elevation maps.

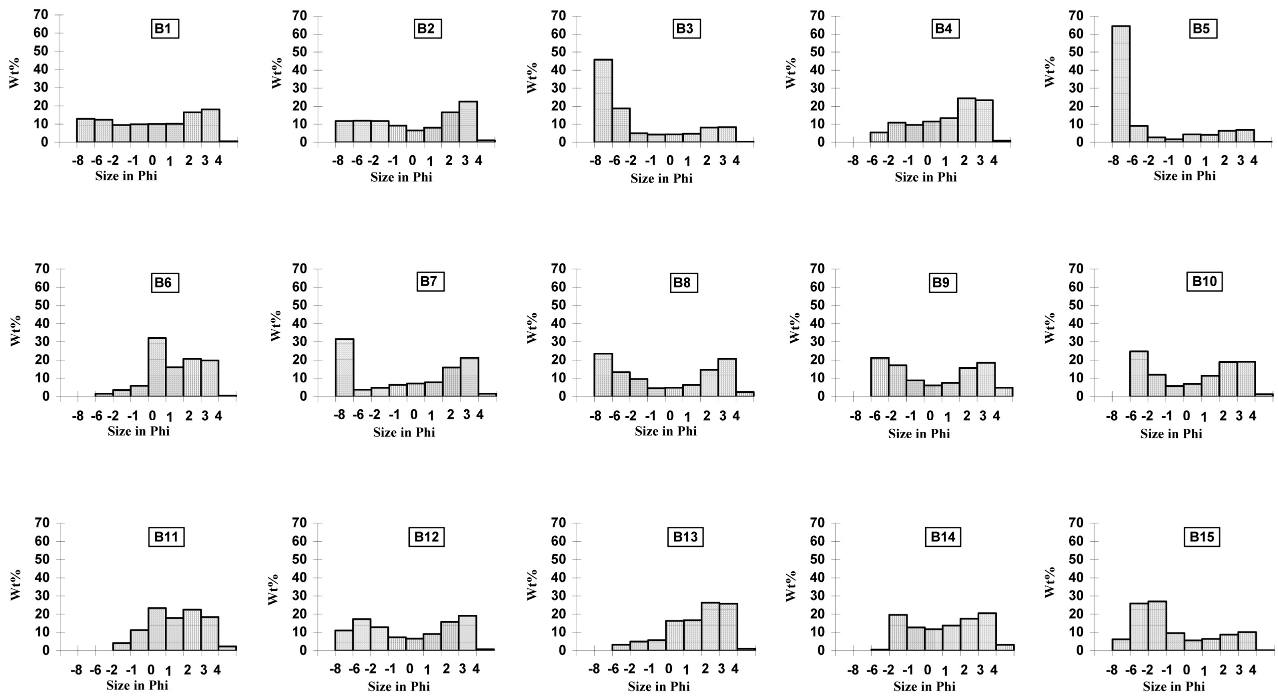


Figure 7. Histograms of samples taken from different stations at Al-Rawdhatain area.

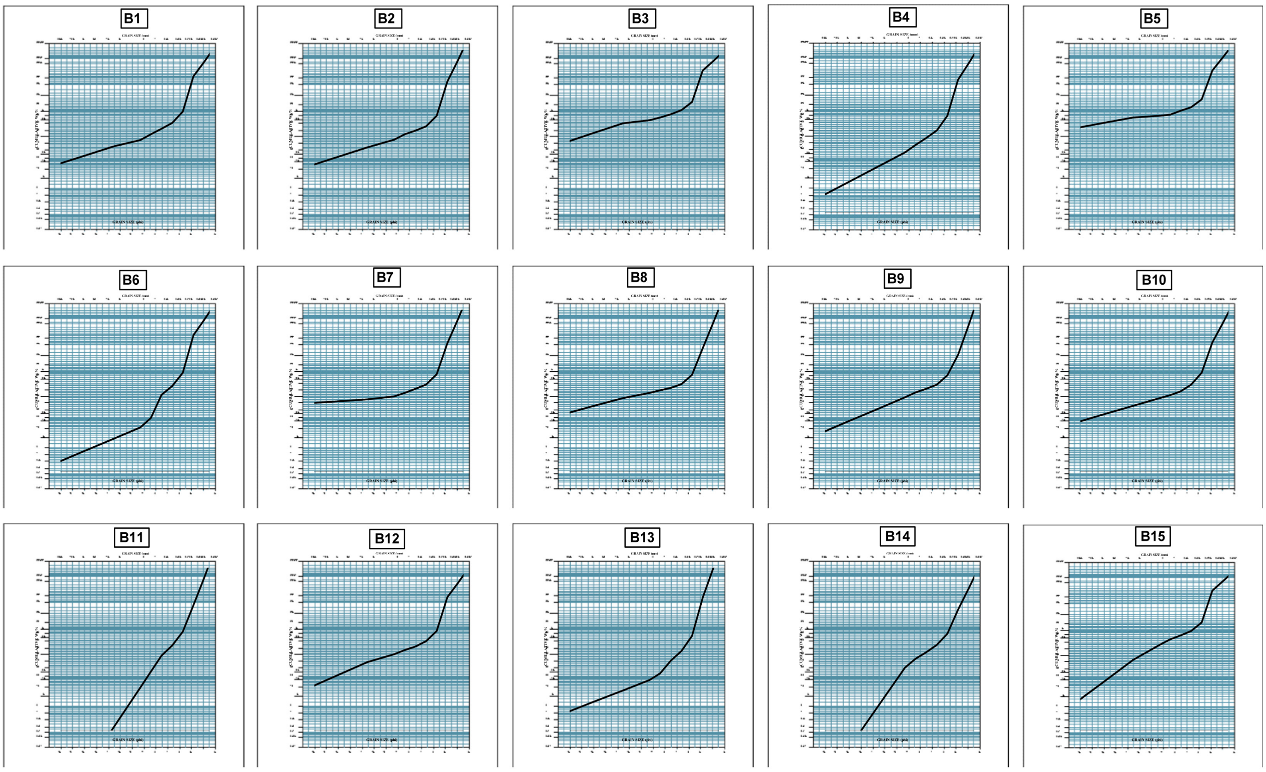
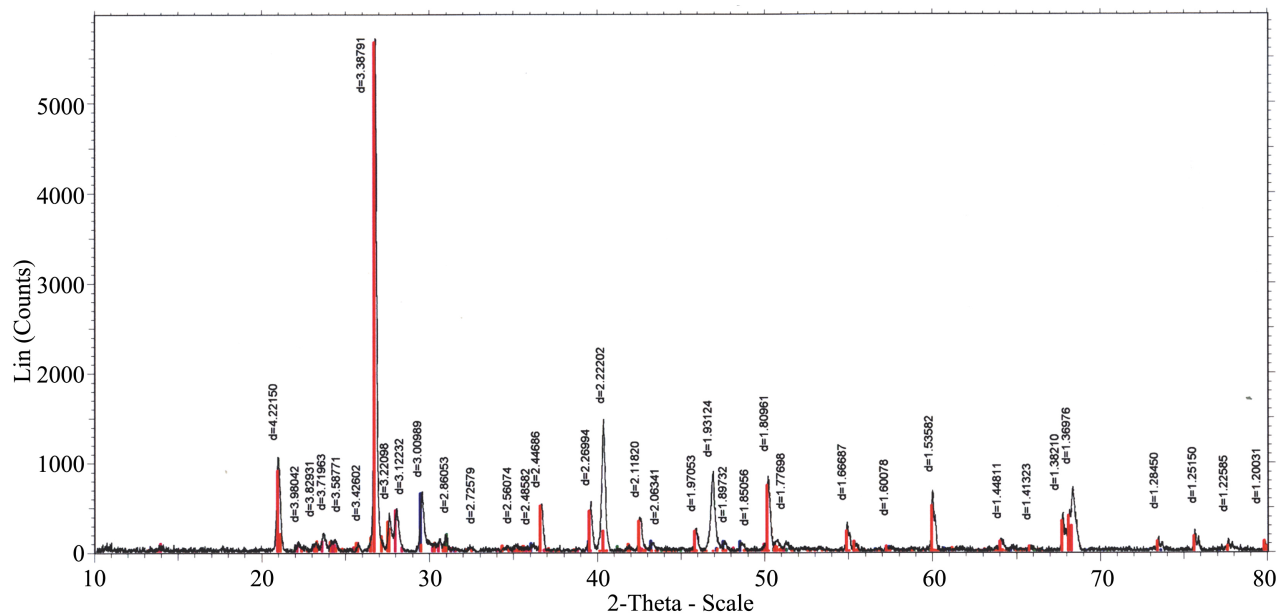


Figure 8. Cumulative curves of samples taken from different stations at Al-Rawdhatain area.



Dr. Adeeba Al-Hurban, E & E Sc. Dept. - File: B1.raw - Step: 0.015˚ - Step time: 0.2 s- Temp.: 25˚C (Room) - WL1: 1.54056 - Creation: 3/8/05 11:03:28 AM

46-1045 (*) - Quartz, syn - SiO_2 - WL: 1.54056 - Hexagonal - a 4.91344 - b 4.91344 - c 5.40524 - alpha 90.000 - beta 90.000 - gamma 120.000 - P3221 (154) - 113.010 - VIc PDF 3.4 - S-Q 58.4%

05-0586 (*) - Calcite, syn - $CaCO_3$ - WL: 1.54056 - Hexagonal (Rh) - a 4.989 - b 4.98900-c 17.062 - alpha 90.000 - beta 90.000 - gamma 120.000 - R-3c (167) - 367.780 - I/Ic PDF 2. - S-Q 11.5%

75-1763 (C) - Dolomite - $CaMg(CO_3)_2$ - WL: 1.54056 - Hexagonal (Rh) - a 4.80800 - b 4.80800 - c 16.02200 - alpha 90.000 - beta 90.000 - gamma 120.000 - R-3 (148) - 320.757 - I/Ic PDF 2.4 - S-Q 2.8%

09-0466 (*) - Albite, ordered - $NaAlSi_3O_8$ - WL: 1.54056 - Triclinic - a 8.144 - b 12.787 - c 7.160 - alpha 94.26 - beta 116.6 - gamma 87.67 - C-1 (0) - 664.837 - I/Ic PDF 2.1 - S-Q 7.7%

76-0918 (C) - Microcline - $KAlSi_3O_8$ - WL: 1.54056 - Triclinic - a 8.57260 - b 12.96180 - c 7.21880 - alpha 90.567 - beta 115.917 - gamma 87.750 - C-1 (0) - 720.875 - I/IcPDF 0.6 - S-Q 19.6%

Figure 9. X-ray diffraction analysis for a sample taken from the desert plain landform at Al-Rawdhatain area.

4.2. Al-Managish

Al-Managish is located in the central part of Kuwait, where it receives most of the drifted sand from the northern area. It is an undulating flat area covered with vegetated sand sheets and most of the area is a restricted area of oil fields. Figure 10 illustrates the topographic, sedimentomorphic and elevation maps of the study area. Comparing the sedimentomorphic map with the other types of maps [42], it is found that most of the smooth sand sheets and desert plains are now changing to vegetated sand sheets. Due to the area being restricted, few wadi fill and drainage systems formed in the area. A total of 27 samples were collected from the surface sediments covering the area and subjected to mechanical analysis (Figure 11 and Figure 12).

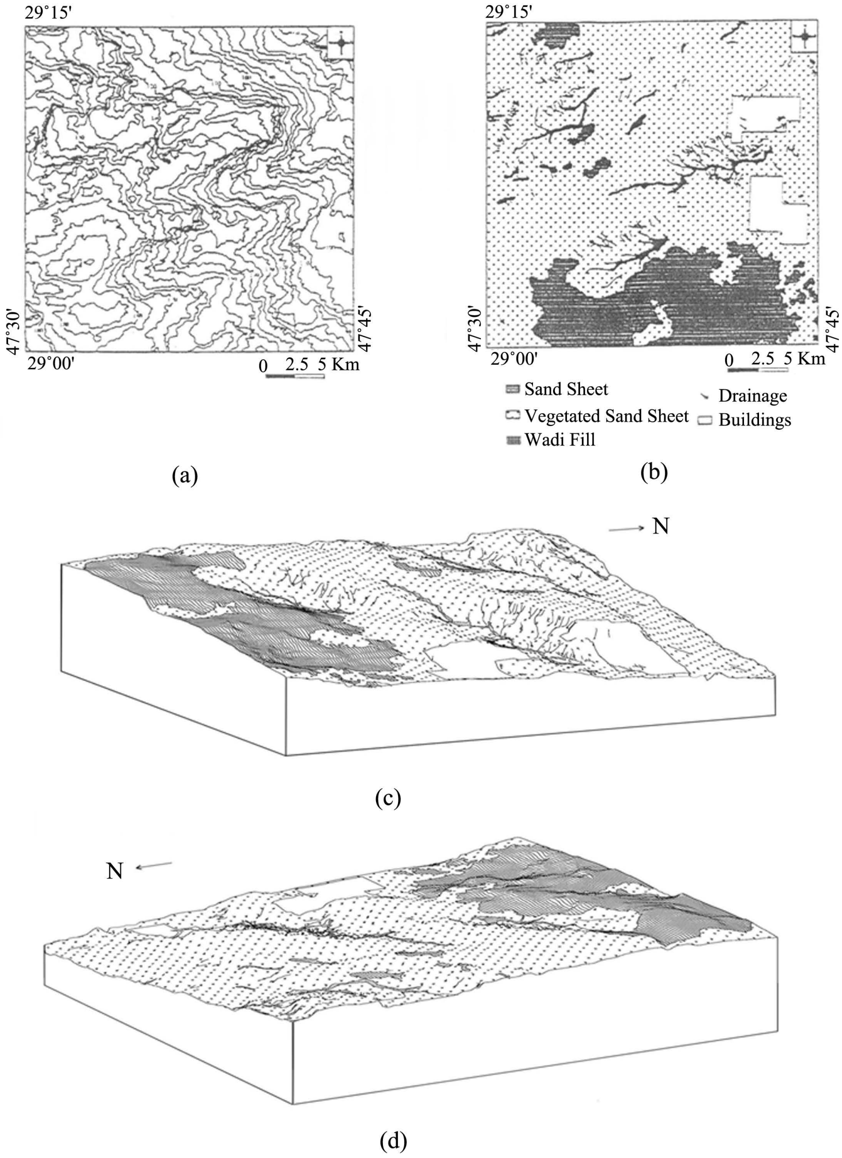


Figure 10. Different types of maps of Al-Managish area: (a) Topographic map, (b) Sedimentomorphic map, (c) and (d) Elevation maps.

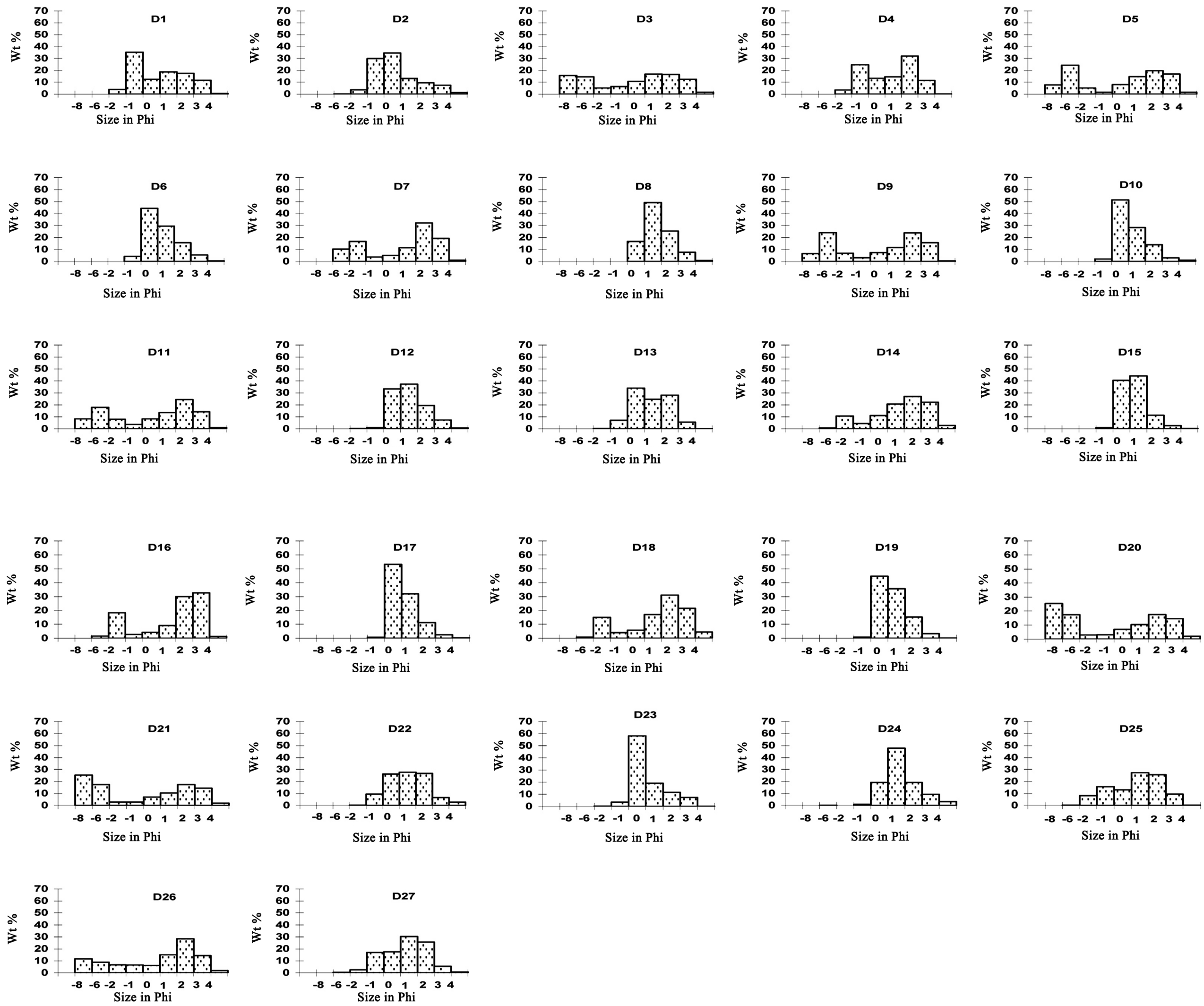


Figure 11. Histograms of samples taken from different stations at Al-Managish area.

A few samples were analyzed by X-ray diffraction to determine the mineral constituents of sediments in the area. Figure 13 shows X-ray diffraction results for one of the most common sediment type in the area. Figure 14 shows the (IRS-1D) satellite images covering the Al-Managish area in 2000 as raw data, histogram equalization, Gaussian stretch image, and linear 2%. The images in Figure 14 need to be validated (ground truthing) for refinement and final delineation of sedimentomorphic classes [13]. Table 1 describes each study area and its landforms and prevailing minerals from X-ray diffraction. Table 2 shows the types and distribution of the recent surface deposits and landforms in the study areas.

4.3. Aeolian Desert Deposits

4.3.1. Sand Sheet

Sand sheets are the most common type of the recent aeolian sand deposits in the study areas [42]. Two main types of sand sheets were identified. These include

Figure 12. Cumulative curves of samples taken from different stations at Al-Managish area.

Table 1. Description of existing landforms in the studied areas.

Name of area	Location	Samples number	Samples number for landform deposits	Most frequent minerals (in avg. wt%)
Al-Rawdhatain (a)	Lat. 29˚45'44"N - 29˚58'19"N Long. 47˚37'30"E - 47˚48'45"E	15	- Desert plain (11) - Wadi fill (3) - Playa (1)	Quartz: 59.1 Calcite: 13.5
Al-Managish (b)	Lat. 29˚00'N - 29˚10'33"N Long. 47˚30'E - 47˚45'E	27	- Sand sheet (15) - Vegetated sand sheet (6) - Wadi fill (6)	Quartz: 74.8 Calcite: 10.8

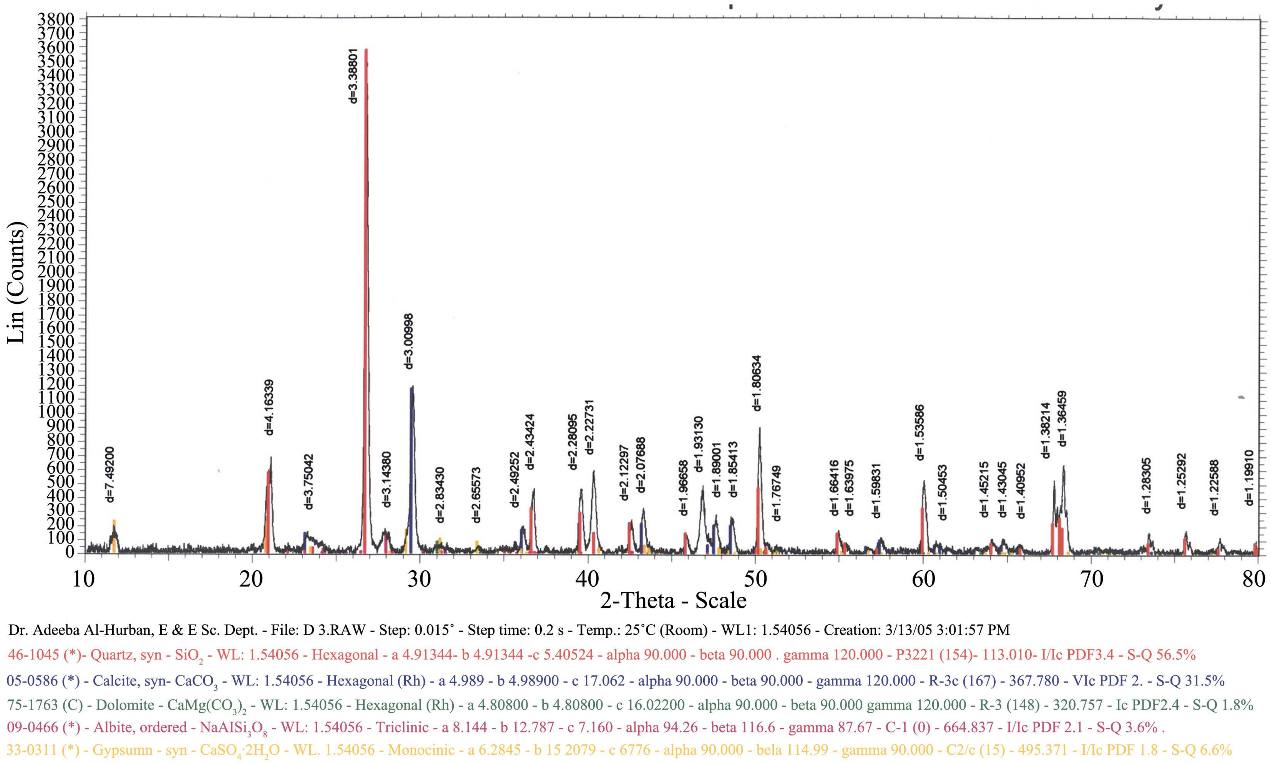


Figure 13. X-ray diffraction analysis for a sample taken from the wadi fill landform at Al-Managish area.

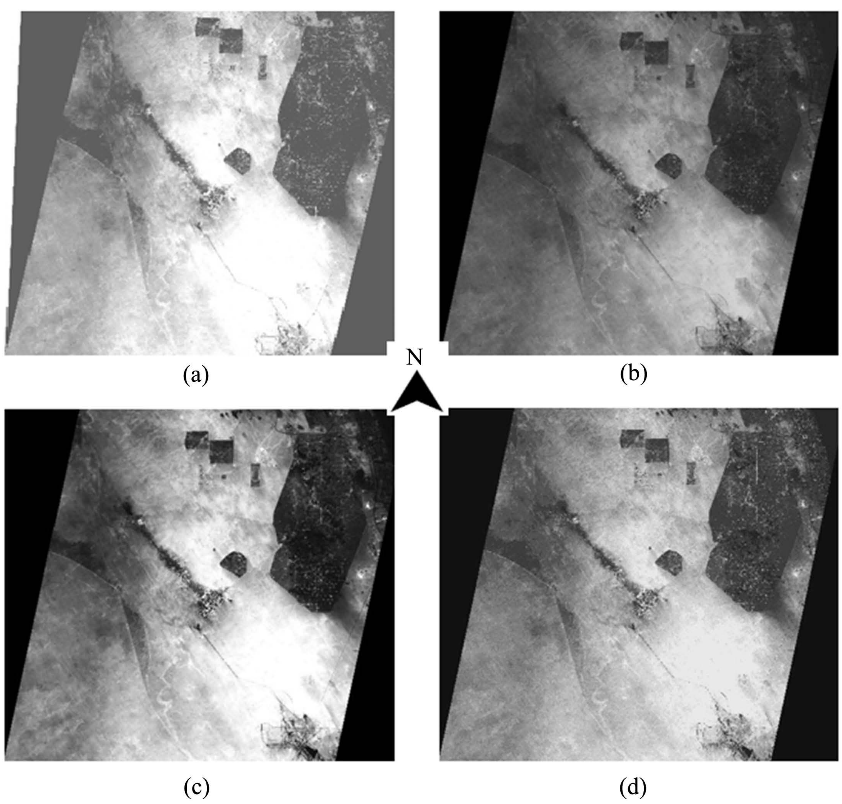


Figure 14. IRS-1D satellite images of Al-Managish area (2000): (a) IRS-1D Raw, (b) IRS-1D Histograms equalization, (c) IRS-1D Gaussian stretch, and (d) IRS-1D Linear 2%.

Table 2. Types and distribution of the recent surface deposits and landforms in the study areas.

Type of deposits	Grain size distribution	Size parameters			
		Mean	Sorting	Skewness	Kurtosis
Desert deposits					
1) Sand sheet					
a) Active	Unimodal	Coarse sand	Poorly sorted	Fine skewed	Leptokurtic
b) Rugged vegetated	Unimodal	Coarse sand	Poorly sorted	Strongly fine skewed	Platy-mesokurtic
2) Sand dunes	Unimodal	Medium sand	Moderately well sorted	Fine	Leptokurtic
3) Wadi fill	Unimodal	Coarse sand	Poorly sorted	Symmetrical	Leptokuritc
4) Playa deposits	Unimodal	Coarse sand	Poorly sorted	Coarsely skewed	Leptokurtic
5) Desert plain deposits	Bimodal	Coarse sand	Very poorly sorted	Coarsely skewed	Leptokurtic

active sand sheets and rugged vegetated sand sheets. The active sand sheet forms a thin blanket of mobile sand that is creeping over other types of recent surface sediments, whereas the rugged vegetated sand sheets are layers formed by the coalescence of small sand dunes and drifts or by free deposition of sand by the wind in a low broad depression. The active sand sheets have an orientation similar to the prevailing NW wind. The grain size distribution of the active sand sheets is of unimodal type. The coarse sand modal class is the most frequent among the analyzed samples. The active sand sheets have an average mean size of 0.59F (coarse sand) and are poorly sorted (1.31F), fine skewed (0.26F) and lepto Kurtic (1.14F) (Table 2).

Vegetation plays an important role in the sedimentation of wind-transported sand since it creates a barrier in its path, and changes in surface roughness over some areas [49]. The vegetation cover in the study area indicates that the soil is sandy in type. In the rugged vegetated sand sheets, the average grain size distribution is of unimodal parameter with a mode of very coarse sand. These sand sheets have an average mean size of 0.63F (coarse sand), 1.31F (poorly sorted), 0.33F (strongly fine skewed), and 0.89F (platy-meso kurtic). The quartz mineral grains are the most predominant among other grains (about 94%) in the active sand sheet, while in the rugged vegetated sand sheet it forms about 60%.

4.3.2. Wadi Fill

The wadi fill represents the most widely distributed aeolian deposit in Kuwait. It constitutes rough irregular hammocks made up of dried outwash deposits, such as sand, silt and clay [18]. Geographically, they are scattered in northeastern areas of drainage basins in all the study areas except Al-Khiran area. These wadis are dry streams that form in the desert environment. The orientation of the existing wadi systems, the sediment transport in the region and the abundance of vegetation in the area act as sand traps that will be filled with transported deposits. The grain size distribution of wadi fill is of unimodal type. The coarse sand modal class is the most frequent among the analyzed samples. The wadi fill is poorly sorted (1.3F), symmetrical (−0.35F) and leptokurtic (0.96F).

4.3.3. Playa Deposits

Playa is a general term used to describe the barren depressions on the lowest positions of a desert basin that periodically collects rainfall and sediments [62] [63] [64]. In Kuwait, playas are called "*Khabrat*" or "*Thamilat*". Such a phenomenon was noticed in Al-Rawdhatain area and in a small, deflated, very shallow and flat circular depression, covered with a thin layer of mud and covered with vegetation. The coarse sand modal class is the most frequent size for this deposit. The playa deposits are poorly sorted (2.04F), coarsely skewed (−0.18F), and leptokurtic (0.69F).

4.3.4. Desert Plain Deposits

Desert plain deposits constitute one of the most recent forms of deposit in Kuwait [18]. It is composed of a mixture of sand, silt, gravel and clay fractions, mostly silty and clay sand, often with gravel admixture. The coarse sand modal class is the most frequent among the analyzed samples. The desert plain deposits are very poorly sorted (11.3F), coarsely skewed (−0.29F), and leptokurtic (0.74F). **Figure 15** shows a comparison between the geomorphological features

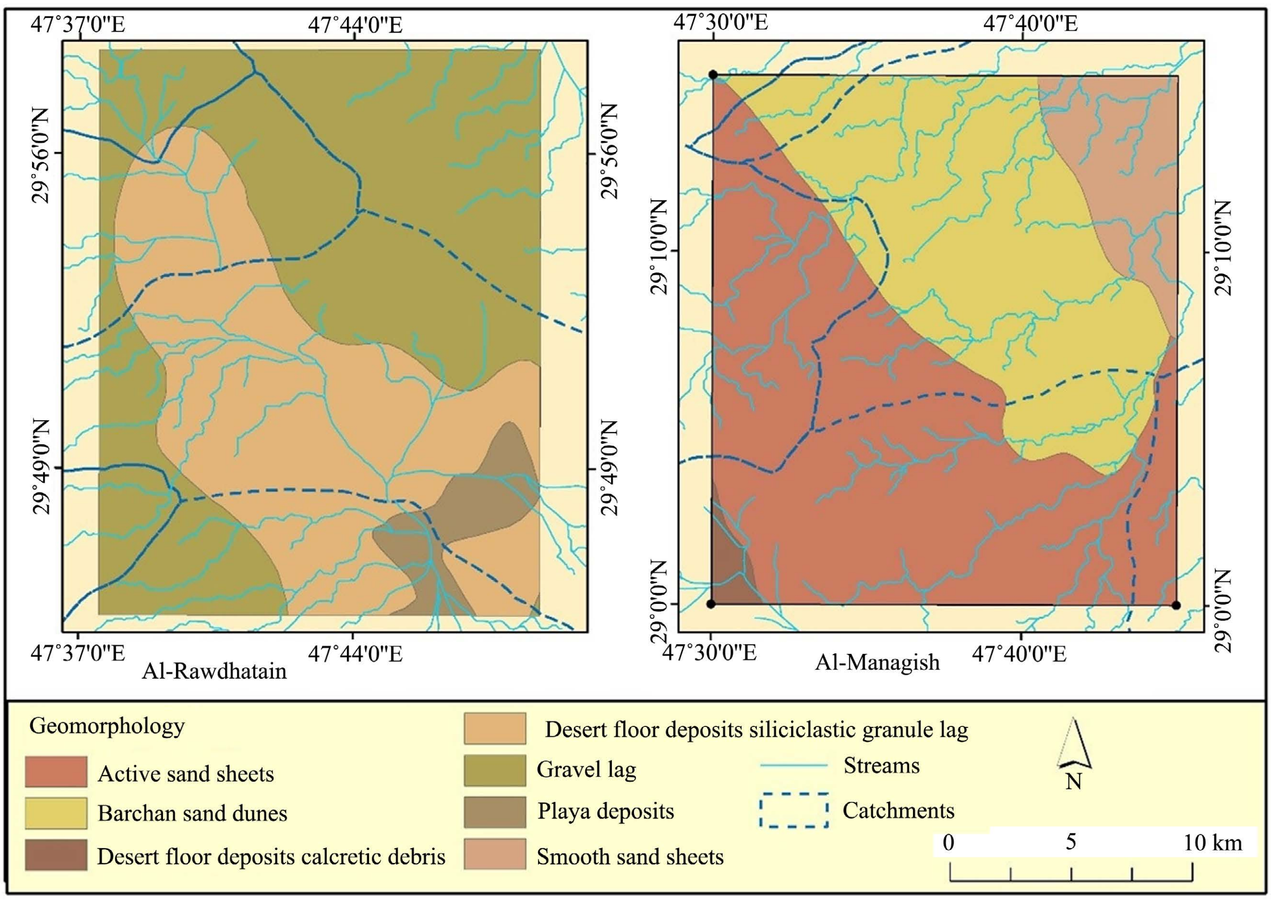


Figure 15. Geomorphological Map for Al-Rawdhatain and Al-Managish areas.

in Al-Rawdhatain and Al-Managish areas, where there are different types of geomorphological features. In Al-Rawdhatain, three geomorphological features represented in the gravel lag plains exist, which are surfaces made of large-sized gravel; the desert floor deposits siliciclastic granule lag and the playa deposits, which appears as an arm extending in the middle of the desert.

In Al-Managish area four types of geomorphological features exist, which are represented in the form of: active sand sheets; barchan sand dunes in the middle of Al-Managish area coming from north of Kuwait; the smooth sand sheets beside the sand dunes; and desert floor deposits of calcretic debris. This shows a variation in the geomorphological features in the two areas despite being of the same desert environment in the state of Kuwait but in different locations in the north (Al-Rawdhatain) and the south (Al-Managish). The geomorphological map of the areas shows a network of valleys, which are filled with water when rain falls between October and April of each year. This drainage network in Al-Rawdhatain area is characterized by its interior drainage in the Al-Rawdhatain depression with the gentle slope in the area. This offers a stark comparison to the Al-Managish area where the lengths of the streams in the drainage network increase and extend to greater distances to drain their water out of Al-Managish area.

4.4. Topographic Analysis, Surface Sediments & Soil Types

Comparing Al-Al-Managish area, which is located in the south-west of Kuwait, with Al-Rawdhatain area, which is located in the north-east, shows a great variation of topographic features. In Al-Al-Managish area, the elevation ranges from 17 to 192 m above sea level, compared to 17 - 92 m in Al Rawdhatain, and this means it exhibits more and more varied topographic features than Al-Rawdhatain area (**Figure 16**). The comparison also shows the closeness of the different topographic belts to each other in Al-Managish area, which indicates the high relief rate compared to that of Al-Rawdhatain area, which is regarded as a depression formed due to the work of geological and erosional factors. Moreover, Al-Rawdahtain is a lowland area, lower than the adjacent areas in the east and the west, forming the oil Al-Rawdhatain depression.

Figure 17 shows the variation of the surface sediments in the Al-Rawdhatain and Al-Al-Managish areas. Al-Rawdhatain witnesses many types of surface sediments like active sand sheets, rugged sand sheets and smooth sand sheets. In Al-Rawdhatain area, the surface sediments groups appear in small areas compared to Al-Al-Managish area in which the surface sediments appear in fewer, much larger areas, represented in desert plain, rugged sand sheets, and small rings of smooth sand sheets. By studying the surface sediments of both areas, variant forms of surface sediments were found with significant variation in Al-Rawdhatain area.

Analyzing the map of soil type and plant variation in Al-Rawdhatain and Al-Managish (**Figure 18**), we can see the variation of the soil forms of Al-Rawdhatain—most of whose soil is composed of the Haplocalcids and Petrogypsids

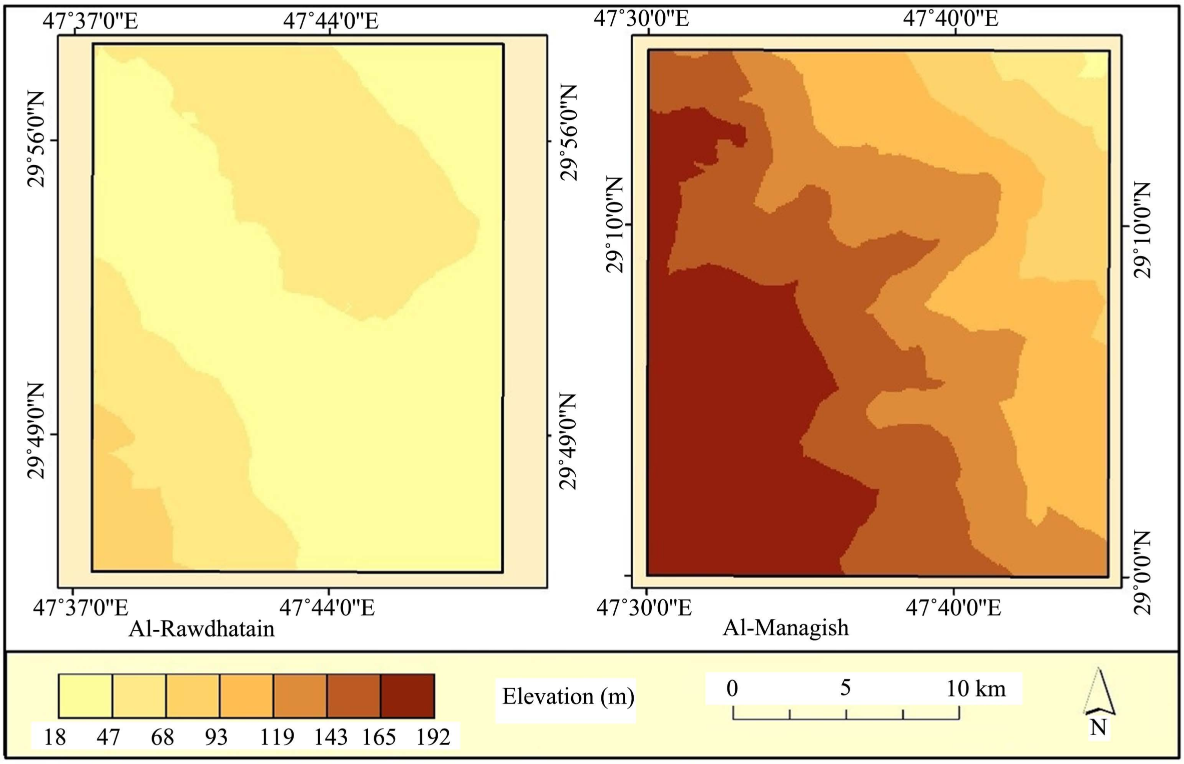


Figure 16. Elevation map of Al-Rawdhatain and Al-Managish areas.

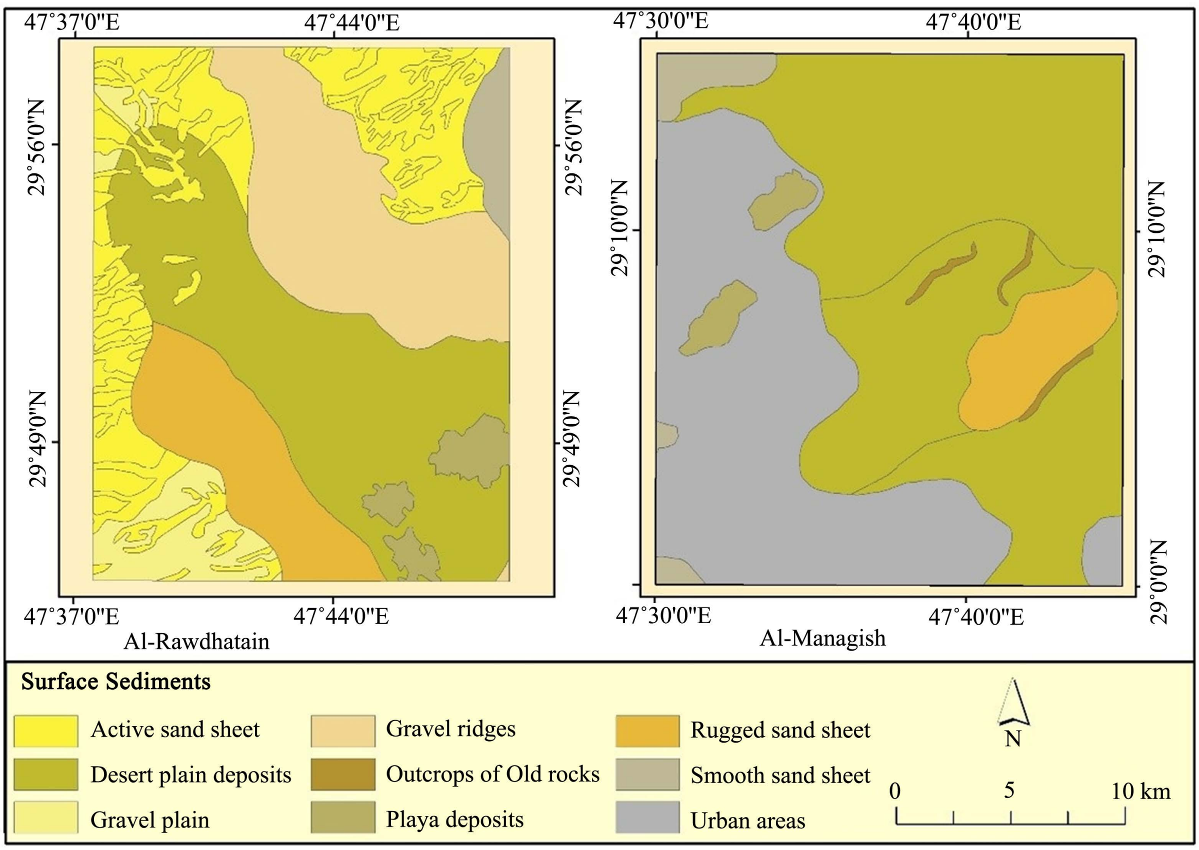


Figure 17. Surface sediments map for Al-Rawdhatain and Al-Managish areas.

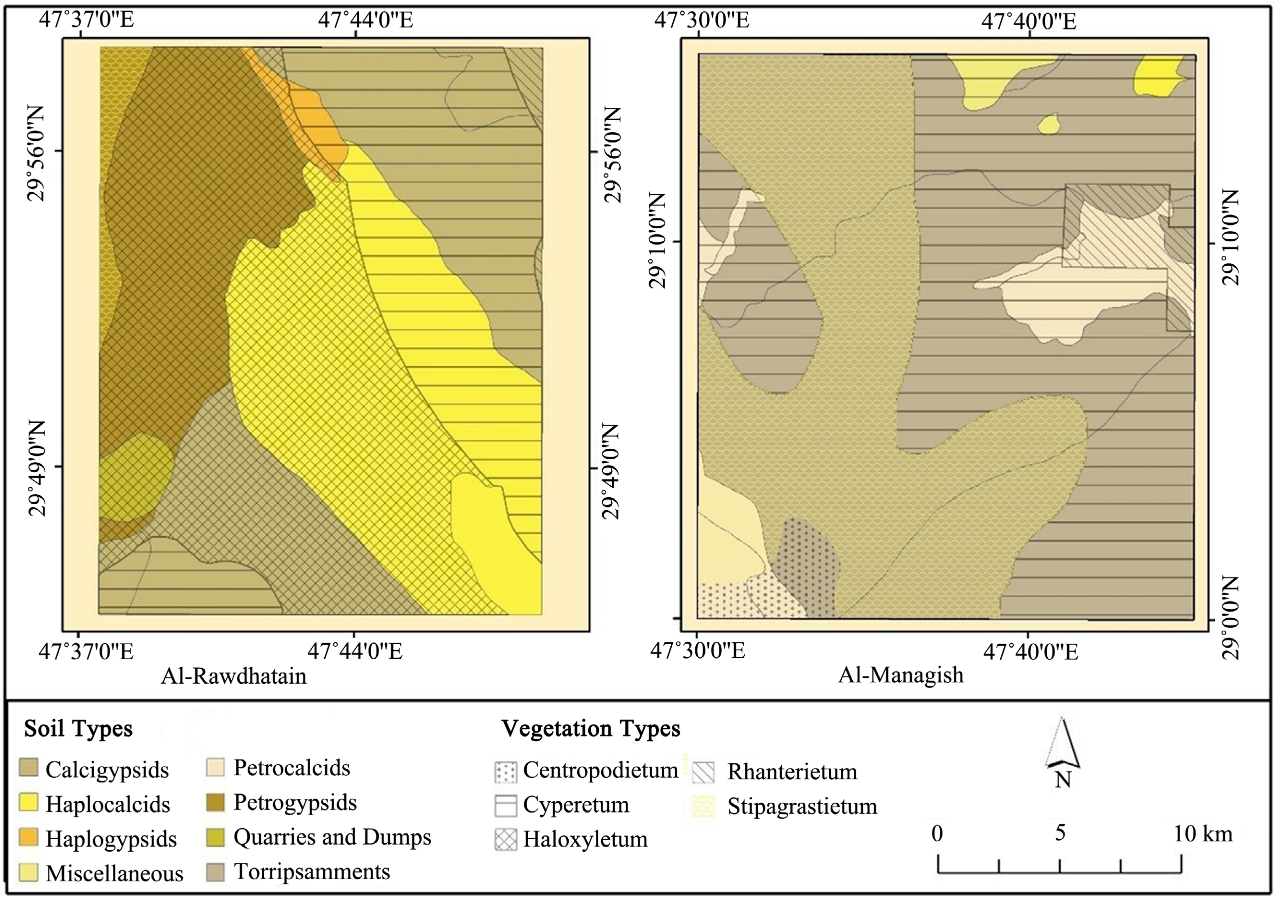
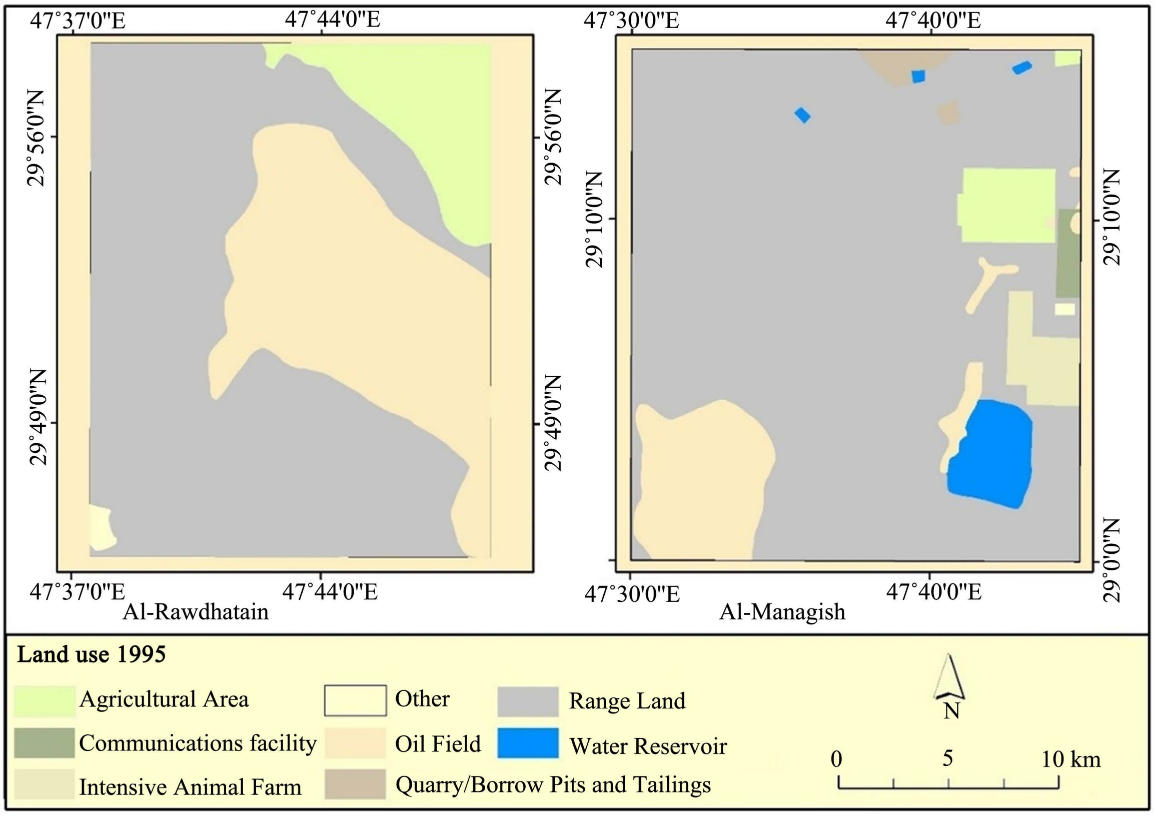


Figure 18. Soil and vegetation types map for Al-Rawdhatain and Al-Managish areas.

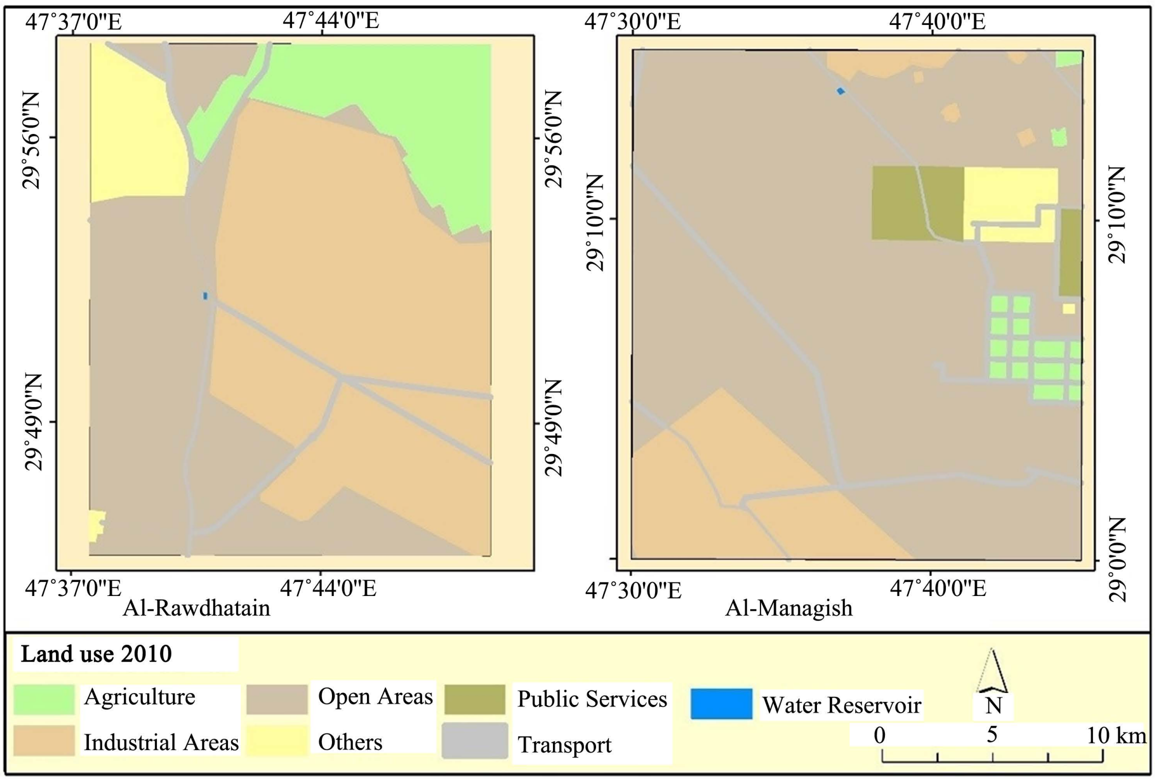
soil types and large parts of Caleigypsids type—and how this compares to the Al-Managish area, where the Torripsamments soil type covers the largest part of the area interspersed with small parts of Petrocalcids soil type. Figure 15 also shows an obvious relationship between the soil type and the natural plants growing over it, where in Al-Rawdhatain area the plant Halayletum grows in the Haplocalcids soil and Cyperture grows in Calcigypsids soil, and the plant types and growth spread in line with the shape of soil types in the area. On the other hand, in the Al-Managish area, whose land is dominated by Torripsamments soil type, the plant Cypertum spreads more inside the area and is interspersed with Stipagrastietum, which indicates how the plants type is related to the soil type that helps in their growth—as well as other environmental factors like the climate and organizing the grazing process. Analyzing the evolution and development of the vegetation cover growth in the Al-Rawdhatain and Al-Managish area shows that Al-Rawdhatain area is richer in vegetation cover than Al-Managish.

4.5. Land Use

Figure 19(a) and Figure 19(b) shows the variation in the land use distribution in Al-Rawdhatain and Al-Managish areas. Figure 19(a) indicates that land uses



(a)



(b)

Figure 19. (a) and (b) Maps showing land use variation in Al-Rawdhatain and Al-Managish areas by time passing.

include oil fields, agricultural areas (Al-Abdali farmlands in the north of Al-Rawdhatain and Kabd farms at the east of Al-Managish), as well as other land uses such quarries and the sand and gravel draquels at the north of Al-Managish area in addition to animal farms, groundwater wells and other public uses. **Figure 19(b)** displays the land use variation in Al-Rawdhatain and Al-Managish areas by time passing, where the oil fields and the fences surrounding the oil extraction areas predominate in both areas, and the rest of the land is a desert full of sand dunes and sheets. A network of roads connecting the areas of Kuwait was constructed in both study areas, which had a great effect in changing the geomorphological characteristics in both areas; the roads cut the valley's network that feed the drainage basins and the mouth of the valleys during the rainfall periods. This is obvious in the growth of some plants, aside from the collected water along the roads and its scarcity and in the lower growth on the other side at the mouth of the valleys that were cut by these roads. **Figure 20** is a map showing how the fields, wells and reservoirs of fresh and brackish water are spreading in Al-Rawdhatain and Al-Managish, which justifies the diversity of water resources in the area and the possibility of development using these wells, where they are used in irrigating the agricultural lands and watering cattle and camels. **Figure 21** is a map showing the surface soil temperature in Al-Rawdhatain and Al-Managish areas. The map indicates the high surface soil temperature in Al-Managish compared to the Al-Rawdhatain area.

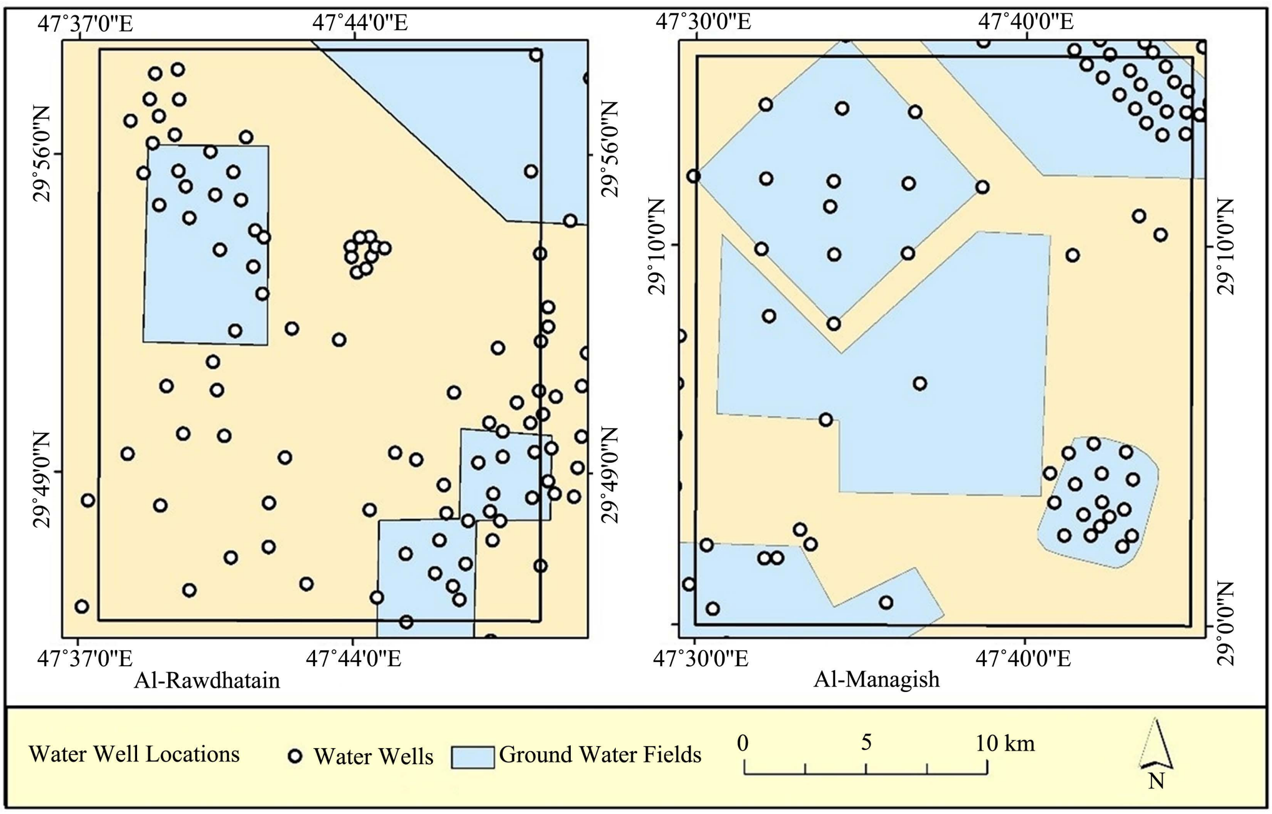


Figure 20. Water well Locations in Al-Rawdhatain and Al-Managish areas.

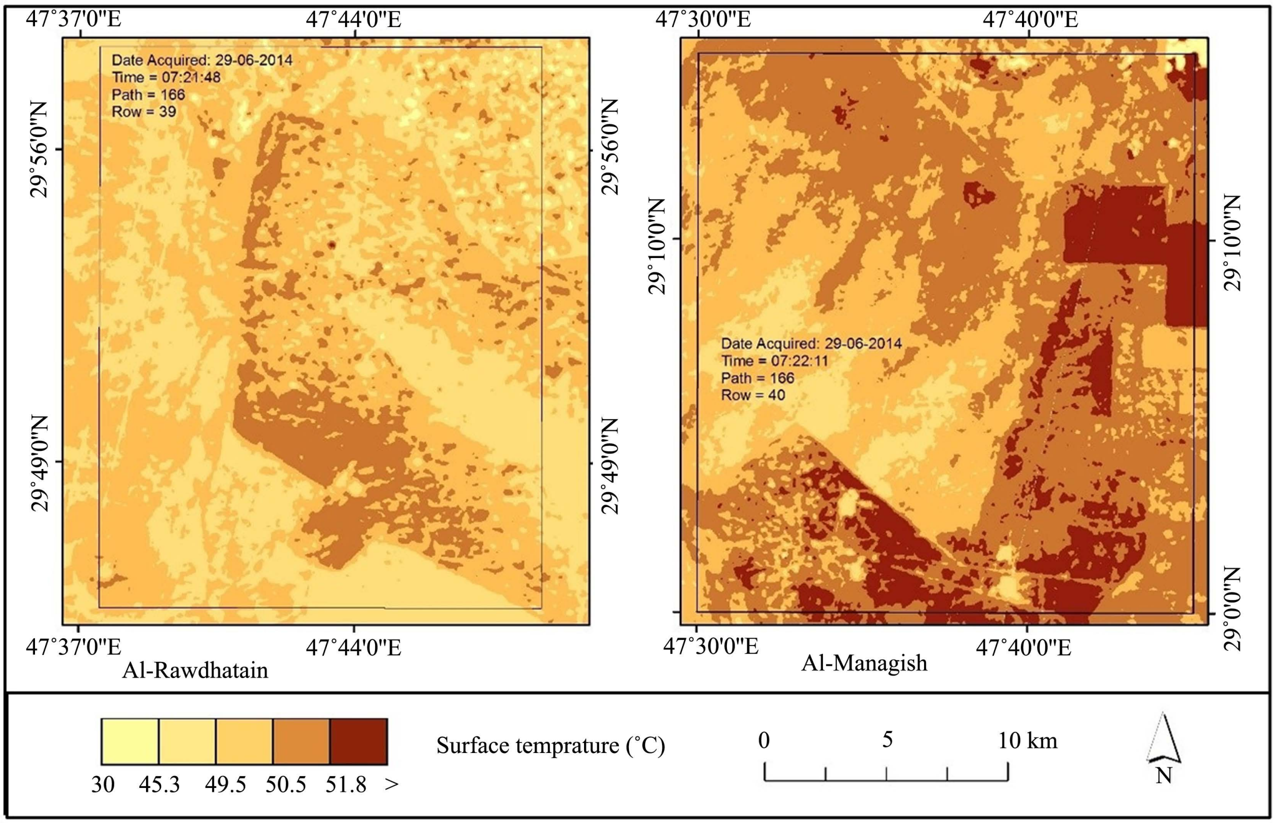


Figure 21. Land surface temperature map for Al-Rawdhatain and Al-Managish areas.

This may be attributed to the existing oil fields and industrial areas in Al-Managish compared to Al-Rawdhatain, which encompasses agricultural lands in the northern areas, as well as the fact that Al-Rawdhatain is relatively low land and the groundwater reservoirs are close to the surface compared to Al-Managish, whose elevation reaches 192 m above sea level.

4.6. Hydrological Impact of Floods on Erosion and Soil Drift

Floods in desert areas during winter work to erode the top surface layer of the soil, where the power of the flushing water leads to soil drift and erosion, particularly in the desert areas on which sand dunes were formed by the effect of sand encroachment during summer. Kuwait's desert areas, particularly Al-Rawdhatain and Al-Managish, were subjected to the danger of floods as a result of the heavy rainfall in November. This caused serious problems and changes in the covering layer of the stream's dry valleys. Therefore, the water which fell on the drainage basins sloping towards Al-Rawdhatain and Al-Managish was evaluated using GIS and WMS, where the amount of rainfall draining to the area was computed along with the flow direction and surface runoff on Kuwait's land.

In the north of Kuwait, there is a group of valleys sloping towards Al-Rawdhatain, which fill with water when rain falls. To the west of Kuwait, there is another group of valleys sloping towards the Al-Managish area. These valleys form a source of running water upon rainfall, where floods are generated in case of heavy rainfall of more than 30 ml per day. This is what happened in November 2018, where more than 50 ml of rainfall was recorded during 24 hours; this was not expected in Kuwait, as the country witnesses an annual mean rainfall of less than 50 ml.

By analyzing the drainage network using WMS software it was indicated that when 50 ml of rain falls during 24 hours, the same as that happened on the 14th of November 2018, an intensive runoff may be generated on the area and the drainage basins are filled with water draining towards Al-Rawdhatain and Al-Al-Managish areas, which could cause the problem of soil erosion.

Figure 22 showing a map of the drainage network in Al-Rawdhatain and Al-Managish. Analysis of the hydrological data for the amount of running water on the surface of the Al-Rawdhatain area (Figure 23) revealed that water flowed at a rate of 47 m^3/s from the drainage basins in the area causing pressure on the drainage network in the area. The discharge peak was recorded at 5040 minutes

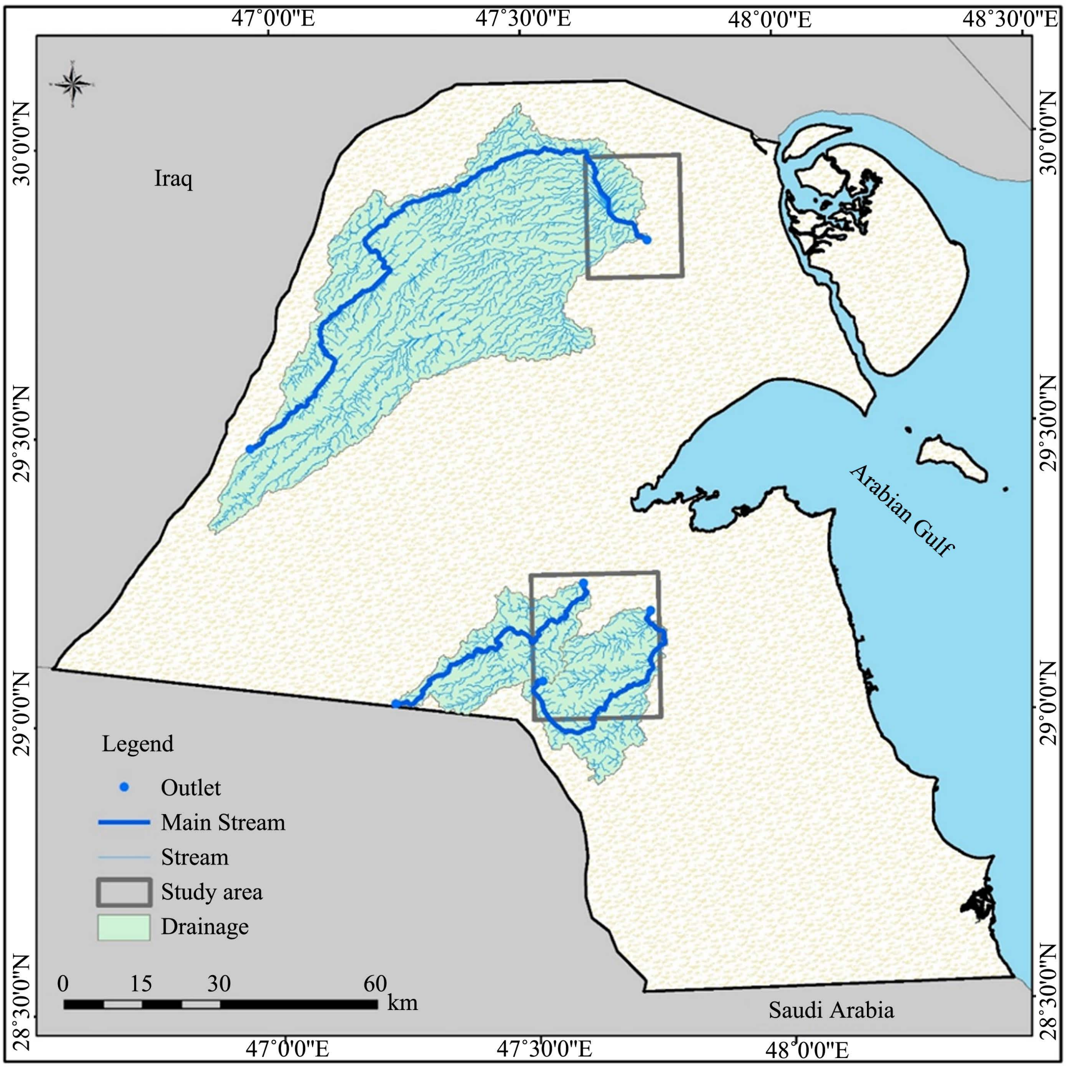


Figure 22. A map showing the drainage network in Al-Rawdhatain area (to the north) and Al-Managish area (to the south-west).

and the net flowing water during precipitation was 15,088,884 m^3. The speed of the running water on the surface was 2.8 m/s, which indicated how dangerous the recorded floods were to the area.

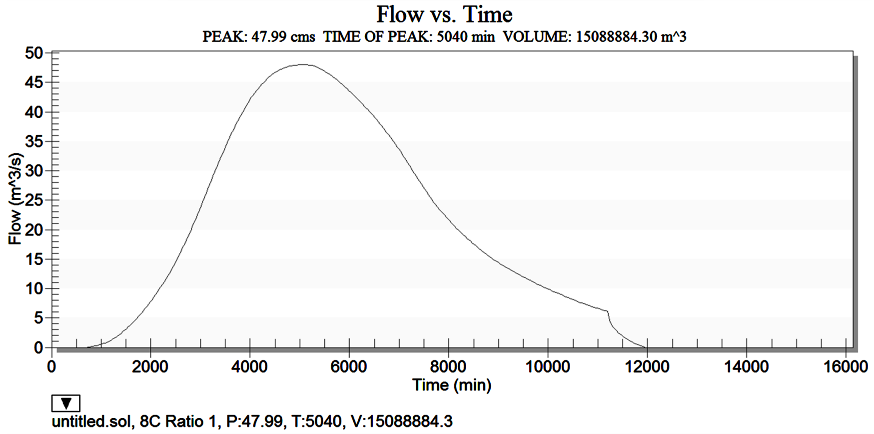
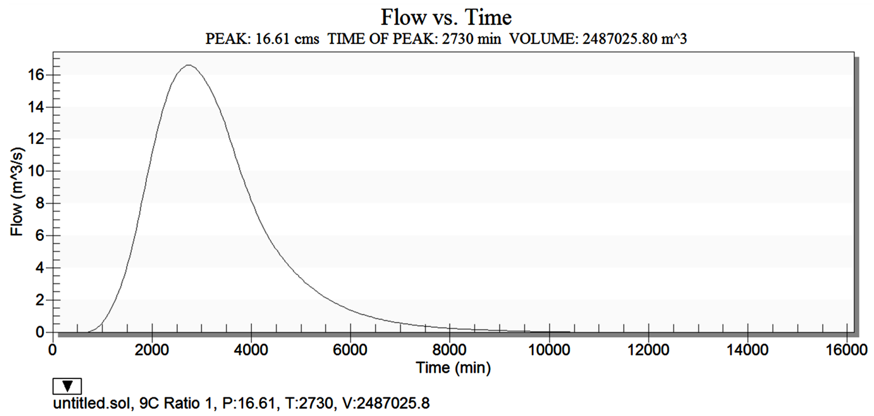
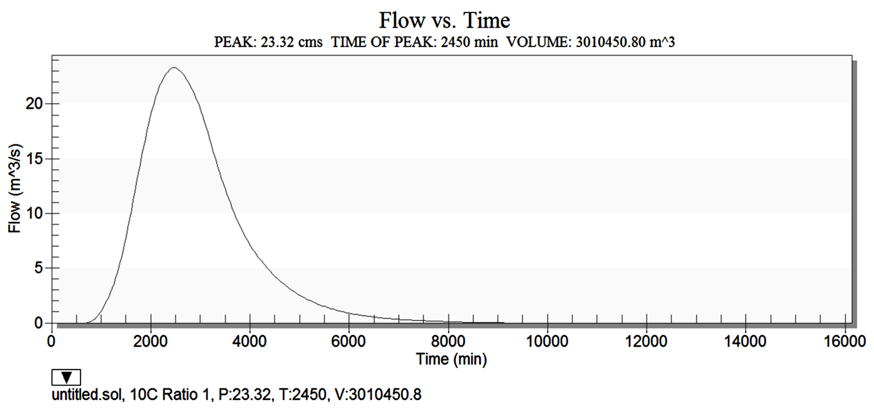


Figure 23. The graphic curve showing the amount of flowing water in the drainage basin in the Al-Rawdhatain area.



(a)



(b)

Figure 24. The graphic curves showing the amount of flowing water in the northern and drainage basins in the Al-Managish area: (a) in the northern drainage basin and (b) in the southern drainage basin.

The recorded amount of flowing water towards Al-Rawdhatain has a direct impact on soil erosion, as the discharge rate exceeded 15 m^3/s in the area, and recorded a discharge peak of 47 m^3/s within 84 hours and an amount of running water of 15,088,884 m^3 causing surface runoff on the area. Al-Managish area is located in a low area where a group of dry valleys slope towards the area; it is in this direction which water flows when rain falls during winter and spring. Analyzing the hydrological characteristics of the drainage basins sloping towards the area indicates the danger of surface soil erosion with the runoff which has a rated peak exceeding 16 m^3/s. **Figure 24(a)** and **Figure 24(b)** shows the graphic curve of the amount of water flowing from the northern and southern drainage basins in the area. In the northern drainage basin the discharge rate exceeded 16 m^3/s within 45 hours and a net amount of 2,487,025 m^3 causing a danger of surface soil erosion in the area (**Figure 24(a)**). Analyzing the hydrological characteristics of the southern drainage basin in the Al-Managish area also showed a threat of surface soil erosion with flowing water. The peak of the discharge rate exceeded 23 m^3/s within 40 hours and a net amount of 3,010,450 m^3 (**Figure 24(b)**).

5. Conclusion

Recent sedimentomorphic maps for the selected study areas were prepared. Aeolian sand sheet deposits are the most frequent recent surface deposits in Kuwait and cover most of the other sediments. The direction of movement of the sand sheets is from NW towards SE as this is the direction of prevailing winds. Both types of sand sheets are poorly sorted because of different types of wind regimes. They both have fine (positive) skewness. The frequency distribution is unimodal for sand sheets and bimodal for vegetated areas, due to the effect of vegetation cover. Sabkhas are subjected to the invasion by sand sheets that are caused by the NW wind, and as a result, the sabkhas are covered by blankets of aeolian sand. Most of the other deposits are poorly sorted, and coarsely skewed, in wadi fill, playa and desert plain deposits, while they are nearly symmetrical and fine in sand dunes. The mineralogical composition (by X-ray diffraction analyses) of the aeolian recent surface sediments revealed that they are mostly derived from the Dibdibba Formation and Tigris-Euphrates fluvial terrace deposits. Quartz is the most frequent component of the studied surface sediments in the study areas (66%). The calcite mineral is also found in small amounts in the study areas (10%). The possible sources of this mineral are the calcretic duricrusts in the Kuwaiti desert. From this study, it is recognized that the study areas have different geomorphological provinces that are covered with different surface sediments. In other geomorphological provinces such as ridges and depressions (Al-Rawdhatain), the main surface deposits are the granule lag and playa deposits. The last part is that sandy flat and undulating areas, such as Al-Managish, are covered with aeolian desert deposits such as active and rugged vegetated sand sheets, sand dunes, and wadi fill. As for the hydrological impact of floods on erosion and soil drift, the study recommends constructing a group of dredges to reduce the flow rate of the surface runoff during rainfall, which will in turn reduce the danger of surface soil erosion and also create reservoirs to store rainwater falling on the Kuwait desert.

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Conflicts of Interest

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

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