Sedimentomorphic evolution of recent surface deposits of Kuwait using Remote Sensing and GIS applications

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Abstract

During the last 30 years Kuwait witnessed sever land degradation due to natural causes and anthropogenic activities, reflected in soil loss, crusting, salinization, oil contamination, and vegetation cover deterioration. Sand and dust storms have acute hazardous environmental impacts on the public health, the economy, and the life quality of Kuwait. The recent surface deposits are classified into two main categories: desert and coastal deposits. The aeolian sand deposits cover the surface of Kuwait’s desert, implying that the wind had reworked the unconsolidated loose desert clastic deposits. It was revealed that the northern desert of Kuwait is receiving excessive sand supply, but the southern desert of Kuwait is experiencing the opposite. This study is based on visual comparison between the 1980s records and field surveys (2001–2014), to investigate the impact of the natural and man-made factors on land degradation, the severe vegetation and surfacial cover loss, and the change in surface deposits. This study compared earlier delineated information on the geomorphic features and sedimentological characteristics from landsat images (1990s, 2000-2004), aerial photographs (1991, scale 1:29,000), geological maps, and topographic maps of Kuwait (1989 & 1994, scale 1:50,000, field observations and spectral and spatial resolution data of the Radarsat, Landsat-7, IRS-1D, ERS, TM, SPOT-4, Advanced Space-borne Thermal Emission and Reflection, and IKANOS data in raw format for Kuwait images for the available years (1989, 1994, and 2000–2004) to detect temporal changes and evolution in the surface sediments. Eventually, a detailed recent sedimentomorphic map of Kuwait was prepared, scale 1:100,000.

Keywords: Sedimentomorphology, Aeolian, Evolution, Land degradation, GIS, remote sensing.

Introduction

Kuwait is located in the northwestern corner of the Arabian Gulf, between latitudes 28°30' and 30°05'N and longitudes 46°33' and 48°30'E, with an approximate area of 18,000 km². It is bordered by the Arabian Gulf from the east, by Iraq from the north and west and by Saudi Arabia from the south. Kuwait is located in a transitional zone between two geological units of the Gulf: the stable Arabian Foreland on the southwest, and the vast compound delta of the Mesopotamian Plain in the north and northwest (Purser, 1973).

Since 1980s Kuwait witnessed severe land degradation and surface deposits changes, which were an ultimate result of either natural or anthropogenic factors. Sandstorms in general and suspended dust in particular are the essential natural problems constituting acute environmental problems in Kuwait, as they adversely affect the economy and life quality Khalaf and Al-Ajmi (1993). Overgrazing, camping and recreation, off-road driving, industrial activities, specifically quarrying, in addition to the severe damage that the area was subjected to during the Iraqi
invasion and liberation with the associated hostilities (1990–1991) constitute the major anthropogenic threats on Kuwait’s environment. Misak et al. (1999) reported that 44 % of Kuwait’s land surface was moderately degraded and 32 % were severely degraded. Gharib et al. (1987) proposed that most probable source of the dust fallout in Kuwait is derived from the southern areas of Iraq, which were drying due to the depletion activities taking place at “Al-Ahwar” by the Iraqi regime in addition to the existing quarries in Kuwait. Accumulated sediment in Al-Ahwar wetlands area are fluvial clay and sand during the Pleistocene, while the Holocene sediments are of fluvial sand, marsh organic sediment, marine sand and silt, peat and fluvial clay and silt (Al-Ameri and Jassim, 2011). They constituted a feeding source of sand, mud, and silt airborne deposits for the load aeolian deflation processes (Vinez and Leonard 2010). Accordingly, the shoreline along the Kuwaiti coast has been significantly degraded, as The Shatt al-Arab’s coastal delta, was no longer fed by the sediments of the Al-Ahwar and has begun to retreat, which threatened the entire geomorphological character of the Northeast Arabian Gulf of being changed.

Excessive grazing can immediately cause sediment destabilization, enrich the dust and sand particles in the storms, expand creeping sand resulting in vegetation cover disappearance and increasing the rate of water erosion (Al-Awadhi et. al., 2003). Off-road vehicles and spring camping have on-site effects involving soil compaction and hence lowering its permeability and destruction of vegetation cover, breakage of armor layer of pebbles and gravels subjecting the underlying or in between finer sediments to be eroded by wind action.

Climate
According to the Koppen classification of the world climate regions declared by Haurwitz and Austin (1944), Kuwait is located in a hot desert zone, and hence have dry climate and arid to semi-arid weather, with a precipitation limited to the cool season from October to May ranging annually from 115 to 120 mm on average. Kuwait’s climate is dry, hot and dusty in summer, relatively cool with low precipitation in winter, mean maximum temperature of 44.7º C in July, mean minimum temperature of 7.7º C in January (Khalaf and Al-Ajmi 1993). Hence, Kuwait became one of the major regions of dust accumulation and duststorms in the world. The prevailing wind directions are northwesterly (43%). Coming in the second place the southeasterly winds (19%) (Dashti, 1993) (Fig. 1).

Vegetation
Kuwait’s vegetation is composed of open scrubs, under-shrubs, perennial herbs, and ephemerals (Halwagy and Halwagy, 1974). Previously five main plant communities were identified: Haloxylon salicornicum, Rhanterium epapposum, Zygophyllum coccineum, Cyperus conglomeratus, and Panicum turgidum by Omar et. al. (1989, 2002). Figure 2 shows A map of Kuwait with the prevailing wind direction, physiographic provinces of Kuwait, and vegetation cover distribution by the integration of soil and vegetation information using GIS. Al-Hurban (2014) stated that a completely new plant species (Eremobleym aegyptiacum) was recorded to grow in the northwestern area of Kuwait, although it is known to be native to Iraq, proposing that the seeds were possibly transported to Kuwait during the northwesterly dust storms.
Fig. 1: Maps of Kuwait showing the prevailing wind directions also the directions of the less frequent and of shorter duration winds affecting Kuwait (after Dashti 1993).

Fig. 2: A map of Kuwait showing the prevailing wind direction, physiographic provinces of Kuwait, and vegetation cover distribution of Kuwait (modified after Khalaf et. al. 1984b and Omar et. al. 2002).

**Physiography**
In general, Kuwait has a flat gently undulating desert plain including a few low hills, escarpments, and depressions with a gradual slope down northeastward and an average gradient of nearly 2 m/km. Physiographically, Kuwait is located between the northern part of the Arabian
Gulf coastal region and the southern border of Al-Dibdibba plain and the lower Mesopotamian plain of Iraq. It is bordered by Al-Dahana sand sea of Saudi Arabia to the west and by the Arabian Gulf to the east. According to Khalaf et al. (1984b), Kuwait can be divided into four physiographic provinces: (a) Al-Dibdibba gravel, (b) sand flat, (c) coastal flat, and (d) coastal hills (Fig. 2).

Kuwait forms part of the interior homoclinal of the Arabian peninsula, as the rocks ranging from Eocene to Recent in age are exposed. Dammam Formation of Eocene age (the oldest) outcrops at Al-Ahmadi ridge and it is constituted of dolomitic micrite containing large irregular dark chert nodules. The formation is uniformly underlain a terrigeneous clastic depositional sequence, locally called the Kuwait Group, ranging from Miocene to Recent in age. Kuwait group is divided into three formations namely: Ghar, Fars, and Al-Dibdibba Formations (Figs. 3 & 4). Al-Dibdibba Formation is a fluvial sequence of sands and sandy gravels and covering most of the northern area of Kuwait (Owen and Nasr 1958; Milton 1965; Fuchs et al. 1968; and Salman 1979).

**Geology**

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 (Owen and Naser, 1958). The surface rocks throughout Kuwait consist of sediments ranging in age from middle Eocene to Recent (Fuchs et al., 1968). Quaternary surficial sediments include Pleistocene gravel and sand, and Holocene sediments including marine sand, coastal deposits, beach rocks, sabkha deposits, desert floor deposits, alluvium and aeolian sands (Fig. 3). The recent surface deposits of Kuwait are considered to be derived from local sources (Khalaf and Al-Ajmi, 1993), which were classified into 6 classes, according to their textural characteristics and field occurrences, as aeolian, residual deposits, playa, desert plain, slope and alluvial fans, and coastal deposits (Khalaf et al., 1984b).

During the Quaternary, the interaction between the climatic effects of the north European Glacial/interglacial periods, the North African Saharan pluvials, and Indian Ocean inter-pluvials controlled the Arabian Gulf. Picha and Saleh (1977), stated that the Quaternary sediments in Kuwait, which mostly cover its surface, are attributed to various terrestrial, deltaic and littoral facies. These sediments include Al-Dibdibbah Pleistocene gravel deposits, and Holocene sediments and overlap Miocene to Pliocene sediments, which are mainly siliciclastic, whereas the Pleistocene and Holocene sediments spreading along the southern coastline of Kuwait belongs to carbonate province of the Arabian Gulf. The northern part of Kuwait is blanketed by deltaic sediments of the Euphrates-Tigris delta, whereas the southern coastline of Kuwait is dominated by oolitic and bioclastic sediments with limited influx of terrigenous material. Holocene sediments include desert surface deposits, alluvium, aeolian sands and beach and coastal deposits such as sabkha deposits, sand shoals, beachrocks and tidal flat deposits (Khalaf et al., 1984a). The regional landscape of Kuwait has been affected to a certain extent by the
Fig. 3: Simplified geological map of Kuwait (after Hunting Geology and Geophysics, 1981).

Fig. 4: Lithostratigraphic succession for the Kuwait region (modified after Misak et. al., 2000).
tectonic movements and a variety of geomorphological processes including prolonged weathering, aeolian and coastal processes during late Pliocene–Pleistocene age.

The main aim of this study is to address the Quaternary sedimentomorphic evolution in Kuwait using the remote sensing images and GIS applications based on the comparison of the older maps of surface deposits of Kuwait that were constructed by Khalaf et. al. (1984b) and Omar et. al. (2002) with the most recent surface deposits prepared by Al-Hurban (2014). This study is also aiming to address the factors played significant roles in the sedimentomorphic evolution of the recent surface deposits of Kuwait.

Methodology

Fieldwork and sampling

included recognition, investigational survey on the study areas, documenting the current on land facts and information, in order to be compared with the earlier delineated information on the geomorphic features and sedimentological characteristics from landsat images (1990s and 2000-2004), aerial photographs (1991, scale 1:29,000), geological and topographic maps of Kuwait (1989 and 1994, scale of 1:50,000), in addition to the field observations. Sampling field trips were conducted for the required investigations and analyses, as surface sediment samples (350) were collected from different areas of Kuwait and were in-field described, photographically documented, and prepared for laboratory analyses.

Laboratory Analysis

The collected samples were subjected to lab analyses including: a) Grain size analysis to investigate the grain size distribution of sediments, as characteristic size parameters were established and their possible geological significance was discussed using mechanical analysis by standard sieving (Folk, 1954), and then obtained data was graphically represented by histograms and cumulative frequency curves; b) X-Ray diffraction for mineral identification in fine-grained sediments and sedimentary rocks; c) mineralogical analysis to understand the genesis and determine the potential sources of the sediments, using microscopic examination to estimate the relative frequency percentages of the main mineral components of the coarse and very fine sand fractions; d) Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) for determining the major, minor, and trace elements in the collected samples (in their liquid phase).

Remote sensing and GIS analysis

In this study, visual digital methods: Landsat-7, IRS-1D (Indian Remote Sensing), SPOT-4 and ASTER (Advanced Space-borne Thermal Emission and Reflection) were used to map sedimentomorphic features. IRS and IKANOS data in raw format for Kuwait images obtained for the study with the available years of 2000 and 2004. GIS ESRI’S ArcGIS8.3 & 9 (ArcView) and some of their extensions (Spatial Analyst, 3D Analyst, and ArcScan) and the Autodesk’s products AutoCAD Map 2000, Autodesk Map 3D, and Autodesk Raster Design ArcGIS software version were used to conduct the GIS functions and analyses. ERDAS Imagine Professional (8.6) software was used where the available first LANDSAT images of 1990s were geometrically corrected based on the images derived from the topographic maps (scale, 1:50,000). Then, their
geo-referenced images were mosaicked and used as a master image to register the second LANDSAT image of 2000–2004. ERDAS Imagine software was used to pick up the different studied locations from the first and the second LANDSAT images. The geo-referenced images were enhanced and used in investigating and updating the sedimentomorphological map of the area. GIS was used to co-register remote sensing data (with the map data and the thematic raster data layers were analyzed using Overlay Technique to derive spatial correlations between the variables (Bonham-Carter, 1997). The images of the study area were analyzed and interpreted using by Integration of remote sensing and GIS Remote sensing techniques to delineate geomorphic zones. A geomorphic map of Kuwait was produced using the integrated remotely sensed data, the extracted GIS ready layers, and the extracted information from previous surface deposits map prepared by Khalaf et. al., (1984b). The LANDSAT images and the different GIS ready extracted layers were overlaid and used for extracting the geomorphological units in the area. Then, the resulting geomorphological map was analyzed and compared with the previously prepared sediment-geomorphic maps to produce the final recent sedimentomorphic map of Kuwait.

Distribution of surface deposits
The aeolian processes in Kuwait are very active and related to the location of Kuwait downwind of the high deflational area of Mesopotamian plain; scanty and irregularity of rainfall with an average of 110mm/yr; and a hot and dry season (May-September) which coincides with the prevailing northwesterly winds. The abundant occurrence of several types of lag deposits (covering most of the northern part), erosion of exposed bed rock (yardangs) and deflation hollow prove the deflation processes clear action (Khalaf and Al-Ajmi, 1993). Khalaf et al. (1984b) classified the recent surface sediments in Kuwait into 6 major groups based on the genesis and mode of occurrence of the sediments: 1) aeolian deposits, 2) residual deposits, 3) playa deposits, 4) desert plain deposits, 5) slope and alluvial fan deposits and 6) coastal deposits and accordingly prepared a sedimentomorphic map (scale 1:1,000,000) to show the distribution of the recent surface deposits of Kuwait (Fig. 5). Al-Hurban (2014) classified, on the same bases of the genesis and mode of occurrence of the sediments, the recent surface deposits into 2 main classes: desert and coastal deposits, which were presented in a new sedimentomorphic map of Kuwait (Fig. 6). Table 1 shows how these types of surface deposits were changed from those occurred in 1980s, as well as the factors that played significant roles in the occurrence of these changes.

Desert deposits
In Kuwait, the desert deposits are the most frequent surface sediment type covering >50% of its desert land surface, which is mostly covered by loose mobile sediments that are in continuous motion and transportation along the surface by the wind action. Kuwait is influenced by 2 sand belts entering the country from Iraq, the larger through Al-Huwaimliyah, and the other through Al-Qashaniya (Foda et al., 1983, 1984). Al-Hurban (2014) recognized six main types of sand deposits: (1) sand sheets, (2) sand dunes, (3) wadi fill deposits, (4) residual gravel, (5) playa deposits, and (6) desert plain deposits.
Fig 5: Sedimentomorphic map of Kuwait showing the recent surface deposits (after Khalaf et. al., 1984b).
Fig. 6: The most recent sedimentomorphic map of Kuwait showing the major classes and subclasses of the surface deposits (Al-Hurban, 2014).
Table 1: Distribution of surface deposits in 1980s and how they were changed during time passing due to different factors.

<table>
<thead>
<tr>
<th>Surface deposits</th>
<th>Distribution in 1980s</th>
<th>Major changes observed or present</th>
<th>Factors responsible for changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desert deposits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Sand sheet</td>
<td>Rugged vegetated sand sheets were distributed</td>
<td>Most of the area was covered with smooth and active sand sheets</td>
<td>Anthropogenic activities (grazing, off-road vehicles, campaign, overexploitation of sand and gravel deposits, and military activities).</td>
</tr>
<tr>
<td>2. Desert sand dunes</td>
<td>Small sizes of barchans</td>
<td>Barchans size increased</td>
<td>Transportation of active sand sheet and the area became more enclosed and less human activities</td>
</tr>
<tr>
<td>3. Wadi fill deposits</td>
<td>Larger size of fill deposits</td>
<td>Smaller in size</td>
<td>Erosion, rainfall in 1990</td>
</tr>
<tr>
<td>4. Residual gravel deposits</td>
<td>Large in size and more abundant</td>
<td>Less abundant and smaller in size</td>
<td>Deflation, more exposed to anthropogenic activities</td>
</tr>
<tr>
<td>5. Playa deposits</td>
<td>In different shapes and depths</td>
<td>Mostly covered with active sand sheets</td>
<td>Increase in aeolian processes due to natural and anthropogenic activities</td>
</tr>
<tr>
<td>6. Desert plain deposits</td>
<td>More and larger sized pebbles with sand drift</td>
<td>Less pebbles and more scattered ones with smaller size</td>
<td>Wind erosion</td>
</tr>
<tr>
<td>Coastal deposits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Coastal sand dunes</td>
<td>Small sandy hillocks around shrubs</td>
<td>Larger in size and more abundant in southern areas</td>
<td>Geology and geomorphology of the area</td>
</tr>
<tr>
<td>2. Sabkha deposits</td>
<td>Extends more in landside and wider along coastal area</td>
<td>Inland sabkhas are covered with sand sheets, and coastal sabkhas are narrower</td>
<td>Movement of active sand sheets</td>
</tr>
<tr>
<td>3. Beach and tidal flat deposits</td>
<td>Narrow belt, small spits</td>
<td>More development of beaches, larger sized spits</td>
<td>High wave and current energy</td>
</tr>
</tbody>
</table>

1. **Sand sheets**
Mostly prevailing in the southern part of the country as well as in considerable size of the northern area of Kuwait. They can be classified into 3 types namely: a) Smooth sand sheets covering most of southern Kuwait with relatively flat unidirectional ripple surfaces and occasionally covered with veneer of residual granules, indicating the northwesterly prevailing wind direction; b) Rugged vegetated sheets, which are layers formed by the coalescence of small sand dunes and drifts or by free deposition of sand by wind in a low broad depression and are mostly covered with extensive vegetated sand drift; and c) Active sand sheets covering considerable areas of Kuwaiti desert in the form of thin blanket of fresh, light-color well sorted sand usually with rippled surfaces and sometimes associated with barchans dunes. According to the type of the active sand sheet, Kuwaiti desert can be divided into 3 main zones: Umm Negga active sand sheet to the northeast; Al-Huwaimliyah active sand sheet in the northwest; and
Southern coast active sand sheet along southern coastal area of Kuwait surrounding and partially covering the inland and coastal sabkhas, where the coastal drifts on the landward side are flanked by the dry sabkha and flat and the active sand sheets (Al-Hurban and Al-Ghadban 2008).

2. Desert Sand dunes
Sand dunes in Kuwait are developed in both desert and coastal areas in 2 major groups: free and anchor. Desert sand dunes belongs to the free type of sand dunes and exist as crescent-shaped dunes named barchans (the most common), occurring as isolated dunes or dune belts (Al Dousari et. al. 2008; Khalaf et. al. 1984 a & b). Goemorphically, they are distributed within the Atraf-Huwaimliyah zone area, Kabd, Sabbiyah, Um Al-Aish, Buhait, and Dhubaiya (Al-Dousari et. al. 2008). The isolated barchans are commonly associated with active sand sheets of Umm Negga (about 1 in quantity) and Al-Huwaimliyah areas. Their morphology and orientation, assure their southeasterly migration, with NW-SE oriented axes, average width of about 150 m and average height of almost 10 m. Unidirectional asymmetrical ripples on the upwind side of the dunes were developed due to the action of the strong winds during storms.

3. Wadi fill deposits
Wadis is the Arabic term for valleys that are dry desert streams. In the northern part of Kuwait they are essentially originated from Wadi Al-Batin (E/NE–W/SW) parallel to Al-Dibdibba fluviatile conglomerate ridges. Wadi fill deposits are mostly of aeolian origin, but some wadis are partially filled with fluviatile wadi fill deposits. These wadis differ in their orientation according to the prevailing wind direction. Such wadis act as sand traps due to the large aeolian sediment transport in the region.

4. Residual gravel deposits
They cover most of the northern part of Kuwait and occur as dispersed blankets of a mixture of multi-sized grains including sand, silt, and clay capped with multi-sized gravels sourced from Al-Dibdibba Formation and Jal Az-Zor Formation (Mckee and Tibbits, 1964). Accordingly, they are subdivided into 3 types: a) Gravel sheet deposits spreading in most of the northern areas as continuous sheets, traversed by parallel dendritic drainage pattern forming wadi fill deposits (Al-Hurban et. al., 2007); b) Slope deposits spreading as continuous sheet covering Al-Dibdibba Formation and Jal Az-Zor ridges, resulting in sub-parallel curved ridges mainly composed of Pleistocene fluviatile Al-Dibdibba conglomerates; and c) Gypcretic and caccretic gravel ridges, as well-developed gypcrete duricrusts, less than 1 m thick, 10-30 cm in common, occur on the desert plain sediments, over the Al-Dibdibba gravel and the calcareous sandstones of Jal Az-Zor Formation and observed at or near the land surface and their clasts are mainly sourced from the deflation of the gypsiferous crust during dry periods, which was formed under lacustrine processes during the Pleistocene (El-Sayed 1993), whereas caccretic duricrust, locally known as “Gatch,” is partly consolidated deposits of a massive bedded calcere and is observed in several parts of Kuwait and consisting mainly of quartz sands with carbonates (calcite and/or dolomite) as a dominant cement (Al-Sulaimi 1988; Al-Sulaimi et. al. 1990).

5. 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 (Neal, 1969, 1975; Motts, 1972). In Kuwait, playas are locally named “Khabrat” or “thamilat.” The playas associated with the desert
 plains are usually circular in shape, flat, and very shallow, while playas associated with wadis are covered with a thin mud layer of vegetated surface (Khalaf et. al. 1984b). Aeolian sand covers entirely some of the playas, which in earlier time used to be surrounded by vegetated sand sheets.

6. Desert plain deposits
In Kuwait, the desert plain deposits are of the Holocene age covering more than 20 % of its surface area and occurring in significant amounts in Umm Al-Aish inter-basin in Al-Rawdhatain large catchment basin occupying one third of the northern part of the northern province of Kuwait, Al-Mutla area and randomly distributed in the western region (Khalaf et. al., 1984b). They are composed of a mixture of sand, silt, gravel, and clay fraction, mostly silty and clayey sand, often with gravel admixture. By comparing the sedimentomorphic map prepared by the study of Al-Hurban (2014) with those of previous studies, it was found that 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 and the playa in the southern corner of the area became somewhat elongated in shape due to erosional activities.

Coastal deposits

They occur in the seashore to the highlands, which constitutes the coastal zone of Kuwait. As Quaternary oolitic limestone coastal ridges in this area separate the extensive and extremely flat areas (known as sabkhas) from the open sea, it is believed that this area was submerged and covered by the sea water in the earlier ages; and the sabkhas surfaces are encrusted by salts, and vertically composed of interbedded mud and evaporite-rich layers, pointing to their occasional flooding by seawater, allowing the development of differently structured algal mats (Khalaf et. al. 1984b). Coastal morphology, environment, composition of the bed rocks, physical and chemical properties of the sea water, and climate and anthropological construction affected the development of the coastal deposits. The terrestrial and marine deposits cover the coastal plain in the northern part of Kuwait, which encloses fluvial depositional features such as alluvial fans in the valley’s mouth and their deposits are consisted of graded accumulation of deposits from coarser-grained (boulders and gravel, at higher parts of the slope) to finer-grained (mud, deposited at the lower areas) (Al-Hurban and Hersi 2008). Al-Hurban (2014) subdivided the coastal deposits into 3 main subdivisions namely: coastal sand dunes, sabkha deposits, and beach and tidal flat deposits.

1. Coastal sand dunes
They develop in the form of a discontinuous belt along the coastline, from the landward limit of the sabkha flat to the debris slope, with a heights ranging from 0.2 to 2.0 m., and are mainly biologically inactive anchored sand dunes (small sandy hillocks) around shrubs or bushes in the northern and southern coastal plains forming morphological phenomena known as nabkhas. They are dominated by locally provided aeolian deposits consisting of silicic grains and rock fragments, mostly derived from the slope sediments of Jal Az-Zor and from other desert deposits (Khalaf et. al. 1984b). The geology and geomorphology of the area control the extension of the coastal sand dunes, distribution, and types.
2. *Sabkha deposits*

Sabkha is the Arabic name for the coastal flat areas extending above the high tidal level and covered by evaporite-rich clastic sediments. Al-Hurban (2004) defined sabkha as “salt flat,” which is part of a landform sequence extending from the shoreline, with an inland basin through a lagoon then to the sabkha. Sabkha deposits involve 2 units: the intertidal flat and sabkha. The coastal sabkha flats occur above normal high tide level in isolated, irregularly shaped patches along the coastal plain. They essentially exist as flat salt marshes expanding further horizontally, seaward and landside, as well as, being bare of vegetation and covered by evaporite-rich clastic sediments. The sabkha deposits are constituted of multi-sized quartz sand, mixed with carbonate mud and occasional crystals of gypsum, covered by salts and gypsum developed during rainy seasons (Al-Hurban and Gharib, 2003). Sabkas in Kuwait are of 2 types: the northern sandy sabkha flats and the southern carbonate-rich sabkha flats. The northern sandy sabkha flats extend along the north coast of Kuwait Bay and Warba and Bubiyan islands, in a narrow strip, separated by some Quaternary coastal ridges from the intertidal zone in the northern areas. The desiccated surface of the sabkha flats witnesses an interbedding of halite and calcite, where some of them were partly eroded from the sea ward by the spring tide overflooding, followed by evaporation and runoff and inland shallow depressions were developed and covered with salt crusts, gypsum, and dried algal mats. Warba and Bubiyan islands offshore sabkhas are characterized by abundant siliciclastic host sediments, absence of algal mat growth, and lack of recent diagenetic dolomite development.

The southern carbonate-rich sabkha flats at the southern coast of Kuwait Bay is bordered by low steep cliffs of Quaternary raised beaches on its landward side covering a very large area around Al-Khiran tidal creeks and separated from the open sea by the Quaternary oolitic limestone coastal ridges extending landward to about 20 km. Their inland side is partially covered by aeolian sand sediments. Their deposits are commonly brown to light gray in color and loose or slightly consolidated, and their surfaces are encrusted by salts, with vertical interbeddings of mud layers and evaporite-rich sand bands in the sabkha deposits (Al-Hurban and Gharib, 2004). In Al-Khiran area sabkha deposits lack dolomite due to the composition of the underlying pre-Pleistocene substrate with hardly any dolomitic material, where Quaternary tectonics provided favorable circumference for the accretion and preservation of oolitic sediments and sabkhas (Picha 1978). The southern sabkha province encloses 2 main types of sabkha deposits: coastal and inland sabkhas (Al-Hurban and Gharib, 2004). Mineralogically, both coastal and inland sabkhas are composed of quartz, feldspar, gypsum, and rock fragments, in addition to skeletal fragment and oolities only in the coastal sabkhas (Al-Hurban and Gharib 2003, 2004).

3. *Beach and tidal flat deposits*

The tidal flat is a nearly level part of the coastal beach, usually extending from the low water mark landward to the more steeply sloping seaward face of the coastal beach or separated from the beach by land under the ocean. The occurrence, width and range of tidal flats vary laterally according to the slope of the coastal area, local indentation of coastline and resonant amplification of the tidal flow with embayment geometry (Khalaf et. al., 1984a). It is covered by muddy sediments with common beach deposits developed at higher elevations on the flat.
is developed in the form a narrow continuous belt extending along the coast with a width varying from about 50 m in the southwest to about 600 m in the northeastern part.

**Results and discussion**

The recent surface sediments occur in the form of a thin veneer within 300km, which gives an evidence that the dust and sand storms are generated within the same domain of Kuwait. The recent surface sediments cover most of Kuwait’s surface, and according to their textural characteristics and mode of occurrence they can be classified into two main classes: desert and coastal deposits. The former are further subdivided into six different subclasses: 1) sand sheet deposits, 2) sand dune deposits, 3) wadi fill deposits, 4) residual gravel deposits, 5) playa deposits, and 6) desert plain deposits, while the coastal deposits are subclassified into three different subclasses: 1) coastal dune deposits, 2) sabkha deposits, and 3) beach and tidal flat deposits. Aeolian sand deposits are the most frequently occurring recent surface deposits covering >50 % of Kuwait’s surface. They exist in different forms including sand sheets, sand dunes, and wadi fill deposits. Their content of sand is thought to be provided by the transportation from older deposits in the form of bedload, as well as, in the same time the finer components (silt and clay) are transported in suspension mode as dust storms. This would justify why by the increasing of suspended dust amounts, Kuwait witnesses the occurrence of substantial deposits of mobile sand.

In the early 1980s small-sized barchans dunes (about 3 m high) were recorded to be migrating within the low-lying areas, whereas recently two types of dunes were recorded to develop namely: 1) the Al-Huwaimiliyah small barchans dunes (recorded in 1984), and 2) a new not previously recorded large barchans dunes (about 10–12 m high), until recently, which might be developed as a result of the Gulf war, in 1990. Military activities during the Gulf war in 1990-1991, subjected the desert surface deposits and soil to severe damages, as the pebbles and cobbleres of the existing desert pavements covering the surface were pressed deep in the sand resulting in the excavation of large amounts of soil on either side of the vehicles track. In addition, Many trenches and pits were dug to hide the equipment, motivating the sand mobilization, as most of these trenches or pits were covered with sand shortly after the war and needed to be excavated. Sand walls (berms) were also constructed along the borders with Saudi Arabia in the south and along the north and west of Jal Az-Zor in the north, providing a good source of sand to be blown away and redeposited 1km downwind from the southern berm, due to the topographic rise, resulting in sand streaks formation or elongated small sand dunes. Many mines particularly in the tri-border area near the western corner of Kuwait were planted causing surface disturbance, as well as laying, recovering and detonating the mines afterwards caused extensive surface disturbances by freeing the sand that was previously protected by wind-polished closely packed residues of pebbles and gravels in the desert pavement, and changing it into mobile sand enhancing the rate of aeolian sand transportation and accumulation. This resulted in a considerable increase in sand dune evolution and development, particularly in the northwestern part of Kuwait. These effects were apparent and assured by the study done by Al-Dabi et. al. (1997) on the evolution of sand dune patterns in space and time in north-western Kuwait.
The decline in the density of the vegetation cover works as an indicator for environmental damages and severe landscape degradation took place since 1980 to recent time. Khalaf et. al. (1984b) prepared a sedimentomorphic map of Kuwait in the early 1980s, indicating that most of the western and southern parts of Kuwait were covered by rugged densely to moderately vegetated sand sheets (RVSS) developed due to the coalescence of nabkhas. In the present time, these RVSS are no longer seen and living desert shrubs (*H. salicornicum*) are rarely recorded. Smooth sand sheets mostly covered by granule lag replaced the pre-existing RVSS, as the dense shrubs stabilizing them were died, leaving their remnants working as barriers trying to restore original occurrence of preexisting nabkhas which were then eroded, and the bedrock was exposed (Fig 7a–c). The pre-existing nabkhas during the early 1980s were extensively eroded in the last 30 years, therefore the sand mounds forming them were deflated and replaced by granule residuals, mostly as granule ripples. Recently, wild life reserves were constructed (e.g., Sheikh Sabah Al-Ahmed wild life reserve) in different areas of Kuwait. Khalaf et. al. (2014) compared the nabkhas in the protected areas in such reserves and non-protected areas, it was found that in the non-protected areas the shrub’s canopy area coverage was dramatically affected and consequently the size of nabkhas developed around them, due to the irrational permanent overgrazing of camel enclosures, which feed only on the leaves of the existing *Nitraria* shrubs. This uprooted plants and inhibited their growth resulting in significant vegetation cover deterioration, which is thought to be a major cause of deterioration and disappearance of the RVSS. In protected areas like Ras Al-Subiayah area and the demilitarized zone along the northern and northwestern border area between Kuwait and Iraq, more intact *Haloxylon* stands were observed, as well as relatively dense vegetation cover. These areas witness well-developed and flourishing *H. salicornicum* nabkhas. The residual gravels mostly cover the northern desert of Kuwait forming a very wide blanket composed of a mixture of gravel, sand, silt, and clay originated from the deflation processes working on the Dibdibba desert, the fine particles are to be carried by wind leaving the coarser particles in the form of lag coarse pebbles, and boulders making a more resistant crust.

**Fig. 7 (a-c):** Block diagrams which are connected with field photographs showing changes in the lithologic units during different periods of time: a. Rugged vegetated sand sheet
(RVSS) during the 1980s; b. Deteriorated RVSS and development of sand sheet with granule ripples recently; c. Smooth sand sheet (Al-Hurban, 2014).

In the northwestern deserts, playa deposits used to be more abundant during the 1980s and more closely associated with drainage systems. Recently, Most of these playas are covered with aeolian sediments due to the higher rates of wind erosion and deposition actions. Misak et. al. (2001) stated that drought conditions are prevailing in Kuwait during the last 2 decades resulting in hypersalinity of groundwater, which in turn prohibits new growth of shrubs. Consequently the soil moisture and humidity had decreased intensifying the deflation processes in the area, which will transport the fine sand particles easily as wind born particles towards the playa surfaces, where they were re-deposited.

In remote sensing, change detection technique is used to identify changes in the state of a surface, phenomenon, or object by observing it at different periods of time. In this study, comparing the geo-referenced images of 1990s and 2000-2004, had detected the changes using the layer stack function of ERDAS Imagine to produce a new stacked images showing the changed areas in colored tone. For example, changes were detected by Al-Hurban et. al. (2007) in Ras Al-Subiyah area (northeastern of Kuwait) from 1990-2001 (Fig. 8a,b). Another example is the changes detected by Al-Hurban et. al. (2013) in Al-Khiran area (southern Kuwait) from 1990-2003, as the changes were mainly concentrated on covering sabkhas by sand in some locations, due to the impact of active sand sheets and aeolian sands, and the demolition of most of the coastal ridges and sabkha deposits by the land development projects taking place in the area (Fig. 9).

**Conclusion**

Conclusively, the aeolian sand deposits cover the surface of Kuwait’s desert, implying that the wind had reworked the unconsolidated loose desert clastic deposits. Land degradation is a very obvious criteria of the northwestern and southern parts of Kuwait, which can be mainly attributed to natural causes including the aeolian processes, soil types and climatic conditions, as well as to anthropogenic activities including overgrazing, campaign, off-road vehicles traffic, and military operations. Overgrazing of the vegetation cover, particularly the Nitraria shrubs around which the major fields of nabkhas occur, played a significant role in vegetation cover deterioration and enhancement of aeolian processes in Kuwait, along with the spring campaigns in the non-protected area due to the clearance of the natural vegetation around the camps (about 3,600 m² on average per camp) (Misak et. al. 2002). Off-road driving and animal traffics on the sabkha surfaces, as well as on the nabkha mounds, resulted in the severe disturbance in the surface sabkha sediments and the nabkha’s sediment cover, which have a devastating effect on the sediment stability. These anthropogenic activities were enforced and enhanced by the prevailing harsh climatic conditions such as drought, high temperature, high evaporation rates, high wind speed, and hypersalinity of groundwater (Khalaf and Al-Hashash 1983; Khalaf and Al-Ajmi 1993; Al-Awadhi and Misak 2001, Khalaf et. al. 2014).

According to the distribution of the areas exhibiting deflation process effects and those exhibiting depositional effects, it was revealed that the northern desert of Kuwait is receiving excessive sand supply, but on the contrary, the southern desert of Kuwait is experiencing the
Fig. 8a,b: Change detection in Al-Sabiyah area: a. change detection during 1990 and 2001; b. change detection from 1990 until 2001 (after Al-Hurban et. al., 2007).

Fig. 9: Change detection from 1990 through 2003 based on landsat images (after Al-Hurban et. al., 2013).
Picha (1978) suggested that favorable conditions for accretion and preservation of oolitic sediment and sabkhas were formed by the action of the Quaternary tectonics in the area’s physiographic and sedimentary developments. The rising sea level in the southern areas allowed the width of sabkha deposits to increase, as they extend to cover a very wide area around Al-Khiran tidal creeks and an extensive, extremely flat area, which is separated from the open sea by the Quaternary oolitic limestone coastal ridges and external landward for about 20 km (Khalaf and Al-Ajmi 1993). Recently, the aeolian sand deposits cover partly a wide area of sabkha flat due to the migration of sand sheets over the sabkha flat, as well as the inter ridge of the sabkha flats shows scattered sand drift features. The extensive prolonged sedimentation in the intertidal flat during transgression phases of the sea water could be the reason for the outward growth of the sabkha plains, as the sediment has partly originated in ancient protected lagoons to seaward and partly formed in place by chemical precipitation directly from sea water (Al-Hurban, 2014).

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