Identifying the Effects of the Gulf War on the Geomorphic Features of Kuwait by Remote Sensing and GIS

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Abstract

Satellite images combined with landform/surface maps are used to identify and characterize changes in the desert surface of Kuwait resulting from military activities during and after the Gulf War of 1991. These changes are producing alterations to the surface sediment and morphological features that lead to environmental degradation.

A geographic information system (GIS) is used to integrate and analyze multi-source and multi-scale data derived from satellite images, maps, and field observations. The GIS is used to identify, describe, and characterize changes occurring in the landform patterns, the nature and extent of land surface change, and their potential impacts on the environment. Postwar satellite images are correlated with prewar field maps, allowing identification of changes in surface sediment types and geomorphic units, focusing on areas showing changes in surface dynamics. Such areas are identified and classified in terms of alterations in the extent of surface sand (postwar sand encroachment) and the impact of oil pollution (formation of layers of tarcrete). The GIS analysis shows that 21.6 percent of Kuwait's area has been affected by the Gulf War, of which 4.4 percent is due to oil pollution and 17.2 percent is due to remobilized sand sheets. These results suggest that a reclassification of Kuwait's geomorphic features is needed to take into account these war-related surface changes.

Introduction

Kuwait is located in the northwestern corner of the Arabian (Persian) Gulf. It covers an area of 17,818 km^2, and its land surface is a generally flat to gently undulating desert plain. Its climate is arid to semi-arid, with an average annual precipitation of 115 mm. Eolian sand deposits are the most frequent type of recent surface deposits and cover most of Kuwait's surface (Khalaf *et al.*, 1984).

The desert surface of Kuwait was severely disturbed during and after the Gulf War due to military activities and postwar clearance of land mines (Al-Ajmi *et al.*, 1994). Three types of major surface changes are particularly evident: (1) disturbance of the desert pavement (a layer of pebbles, one particle thick, that protects the sandy soil from wind erosion), destruction of the sparse vegetation cover by military activities (El-Baz, 1992a), and excavation and trenching by troops, (2) deposition of oil and soot on the desert surface from the plumes of the oil well fires, which mixed with sand and gravel and hardened into a layer of "tarcrete" (El-Baz, 1994), and (3) formation of over 300 inland oil lakes from damaged oil wells (El-Baz, 1992b; El-Baz and Al-Ajmi, 1993).

Figures 1a and 1b show a prewar (1989) and postwar (1991) Landsat TM image of Kuwait City and the Greater Burgan oil field. A comparison of these images shows the magnitude and type of surface changes that occurred in this part of Kuwait. These changes are mainly reflected by the tarcrete layer that extends from the oil field towards the southeast, in the direction of the prevailing wind. Bright areas in Figure 1b correspond to a thin layer of active sand or sand sheets, which suggest the mobilization of sand and its movement from northwest to southeast following the main wind direction.

Previous studies have focused on mapping of these surface changes in terms of assessing the damage caused to the environment (Koch and El-Baz, 1993; El-Baz *et al.*, 1994a). However, it is expected that the remobilization of vast amounts of sand, and the surface cover of tarcrete, is having a major impact on the geomorphology and the distribution of surface sediments in Kuwait (Al-Ajmi *et al.*, 1994). Desert environments are very fragile ecosystems which react to surface disturbances with changes in their erosional/depositional dynamic setting. Factors that have a severe effect on desert surfaces are well known, and are mainly due to damage caused by off-road vehicle traffic (Webb and Wilshire, 1983), as well as the construction of trenches, pits, and sand walls for military purposes (El-Baz, 1994).

Satellite images (e.g., Landsat TM multispectral and SPOT panchromatic) have, because of their high spatial and temporal resolution, been used increasingly to identify surfaces disrupted by military activities. Their regional scale coverage allows rapid and regular monitoring of the effects of such military activities. Most studies deal with relatively small-scale surface disturbances, and are generally based on identifying the level of surface disturbance in military training areas by calculating the total number of vehicle tracks per unit area for selected test areas (Linn and Gordon, 1993; McCarthy *et al.*, 1996). The present work, however, differs in that it presents a computer-based methodology to establish the geomorphic impact of military maneuvers on desert surfaces at regional scales (> 10,000 km^2), and to relate types of disturbance to their effect on geomorphic surfaces and surface sediment properties.

To establish the nature, extent, and effect of war-induced

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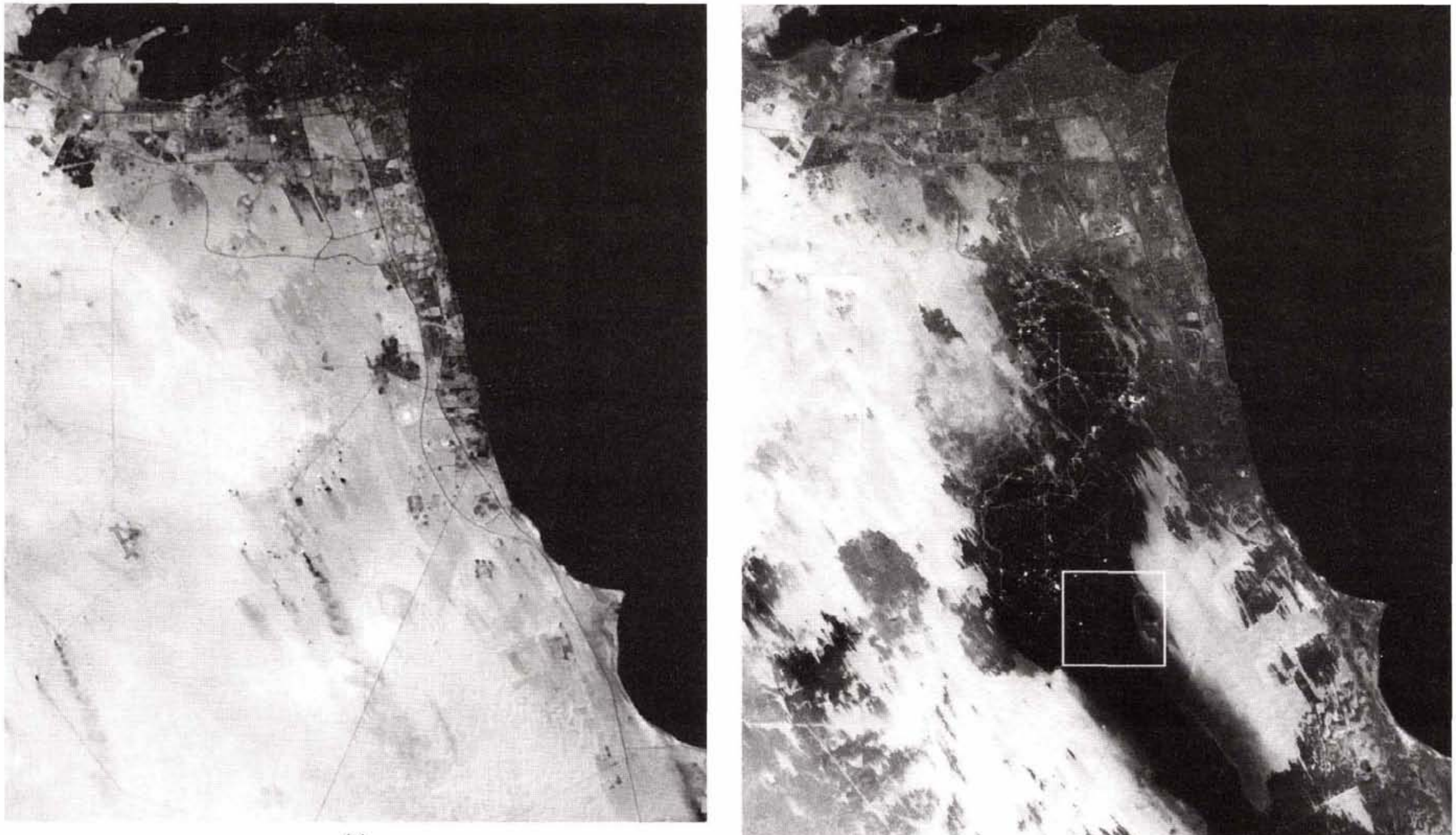


(a) (b)

Figure 1. (a) Prewar Landsat TM image (25 June 1989, band 4) of southeast Kuwait showing Kuwait City and Greater Burgan oil field due south of the city. Image covers an area of 70 by 84 km. See Figure 5 for location. (b) Postwar Landsat TM image (14 November 1991, band 4) of the same area, showing oil polluted sand surfaces in black and sand sheets in bright tones. White box shows location of SPOT image shown in Figure 4. Image covers the same area as in (a). See Figure 5 for location.

changes, a comparative study of prewar and postwar desert surface characteristics is essential. In this paper, a combination of remote sensing techniques and GIS methodology is used to identify and correlate surface changes based on data derived from satellite images, maps, and field observations. The results obtained from this correlation are further analyzed in terms of their possible implication to the overall geomorphic dynamics of Kuwait.

Methodology

In a previous study, remote sensing techniques were used to generate two sets of thematic maps which cover the entire surface area of Kuwait (El-Baz *et al.*, 1994b). One set depicts surface reflectance changes that were attributed to the effects of military activity, and the second classified the types of surface materials as portrayed on satellite images shortly after the war.

In the present work, both sets of maps are correlated and used in conjunction with prewar maps to further enhance their interpretation. The combination of multi-source and multi-scale data is best achieved in a geographic information database where all maps are registered to a common geographic coordinate system. Data input is performed by digitizing or scanning maps, entering non-spatial data (i.e., attributes or properties of spatial features) through text files or keyboard, or by reading in data files using appropriate format conversion filters. Data fusion is, however, not a simple task. Problems due to differences in map scale, data sources, and methods of acquisition need first to be overcome before combining the data for analysis. Some of the problems encountered during this research are addressed below and possible solutions are suggested.

Satellite Images and Map Data Integration

A GIS database was constructed to include the following data sets (Table 1): Landsat Thematic Mapper (TM)-derived surface change map and classification map, SPOT panchromatic images, topographic maps, geomorphic map, and surface sediment map of Kuwait. All the map layers were registered to topographic maps at the scale of 1:50,000, which were selected as a base because of their spatial accuracy and their Universal Transverse Mercator (UTM) coordinate system, which facilitates length and area calculations.

Generalization effects always occur when maps of different scales are compared, and this may result in a modification of the statistical and geometric properties of the digital map data, thus affecting the performance of GIS operations by introducing error (João *et al.*, 1993). The use of topographic base maps at a larger scale than apparently necessary, and generated by a single source, is recommended to minimize these effects.

Prewar maps depicting the geomorphology of Kuwait (Khalaf and Al-Ajmi, 1993), zones of sand encroachment (Al-Ajmi *et al.*, 1994), and the distribution of surface sediments in Kuwait (KISR, 1980) were digitized at the scale of 1:250,000 and incorporated into the GIS database. These maps serve as a baseline to which postwar satellite images and their derived products are compared.

TABLE 1. LIST OF GIS DATA SET USED IN THIS WORK

Map	Scale/ Resolution	Date	Source
TM Change Map	30 m	1989–92	Abuelgasim *et al.* (1998)
TM Spectral Class Map	30 m	1992	Al-Doasari *et al.* (1998)
SPOT Oil Lake Map	10 m	1992	Koch and El-Baz (1993)
Surface Sediment Map	1:250,000	1980	KISR (1980)
Sand Encroachment Map	1:250,000	—	Al-Ajmi *et al.* (1994)
Geomorphological Map	1:250,000	1980	Khalaf and Al-Ajmi (1993)
Topographic Maps	1:50,000	1991	Ministry of Defence, UK

The spatial resolution of SPOT panchromatic images is 10 m, and that of Landsat TM images is 30 m, nearly comparable to a map scale of 1:50,000. However, the spatial resolution of the satellite data is not compatible with that of the prewar maps (1:250,000), which were enlarged during the map registration process to match the scale of the topographic maps. Because the original scales of the two data sets are incompatible, an intermediate scale of 1:100,000 was chosen for performing correlation analysis between them, because the present study has the aim of detecting and mapping surface disturbances at a regional scale. By downscaling the prewar maps, the information content is certainly not improved, but results in a higher level of generalization of geomorphic processes. Conversely, upscaling (degrading) postwar thematic maps (e.g., classified satellite images) may result in information loss (by aggregating spectral classes).

The 1:100,000 scale is the smallest that can be used without losing spectral class information. Biophysical and geomorphic processes are scale dependent. Thus, the type of processes examined in this paper is clearly restricted to those detectable by the satellite image resolution. Because the primary motivation of this work is to establish the environmental impact of human-induced surface changes at a regional scale encompassing the total surface of Kuwait, emphasis was placed on geomorphic process occurring at this level, i.e., large scale eolian processes, involving the entrainment, transport, and deposition of sediments by the wind. The interaction between wind and surface deposits is the predominant geomorphic processes in Kuwait due to a general lack of vegetation cover.

Another factor that made the construction of the GIS database laborious is the relatively homogeneity of Kuwait's land surface, which has few elevated points. Fixed topographic features that are easily identifiable are good control points for registration purposes. Only the eastern part of Kuwait shows a dense network of infrastructure and appropriate topographic features because most of the urban areas and oil fields, as well as the coastline, are located in this part of the country. The western part of the country is characterized by a relatively homogeneous and featureless desert with few roads. Consequently, fewer control points could be selected in that area, which decreased the positional accuracy between master and slave map layers in these areas. However, at a country-wide scale, these errors are averaged out, and an acceptable fitting (RMS error < 100 m) of each map layer was obtained.

Data Correlation

Surface changes were mapped from prewar (1989) and postwar (1992) TM images using a method described in El-Baz *et al.* (1994a; 1994b). According to these authors, the regression technique generates the best change detection results because it eliminates the effects of any atmospheric changes between the two dates, which may cause problems in the detection of surface change. Substantial atmospheric changes were caused by smoke emanating from burning oil wells. The regression technique was carried out for two spectral bands (TM bands 5 and 7), and the resulting change images were thresholded following a method described by Abuelgasim *et al.* (1998), which uses an unsupervised k-means clustering algorithm to group various types of altered areas based on their spectral similarity. The classes generated by this procedure were subsequently aggregated based on field observation, resulting in three main categories (no/little, minor, and major change, with the last category being subdivided into thin and thick tarcrete, and active sand). Because this work deals with the detection of change at a regional scale rather than the amount and magnitude of change, a more detailed classification of change was not thought necessary. The three categories are represented on the image as areas of either increased, equal, or decreased spectral reflectance. In general, those areas corresponding to an increase in spectral reflectance are sand sheets and those corresponding to a decrease of brightness are oil polluted sands or tarcrete (compare Figures 1a and 1b).

A second image-derived map was used to further define the type of surface deposits that fall within each of the three change categories mentioned above. A k-means classification of postwar TM images (1992) combined with field observation was produced by Al-Doasari *et al.* (1998), and corroborated by spectral field data (Al-Doasari, 1994). Spectrally similar surface materials were grouped together in this map, and labeled in terms of 18 different surface deposits after field checking. The categories corresponding to sand sheets (active, semi-active, vegetated sand sheets) and tarcrete are directly related to the effects of the Gulf War.

A third map, showing the prewar surface sediment type distribution (compiled by the Kuwait Institute for Scientific Research (KISR) in 1980), was compared to the satellite image maps. This map depicts 21 types of surface deposits, and was used as prewar reference data for characterizing the nature of subsequent surface sediment changes.

In order to overcome data incompatibility resulting from the use of different classification schemes, the original categories of each map were grouped into fewer categories corresponding to those derived from other sources (see Data Analysis below). This operation was performed on the basis of knowledge obtained through image interpretation and field investigation.

Results

Data Analysis

Since the end of the Gulf War, a substantial increase in eolian activity has been observed in Kuwait, which can cause serious problems to agriculture, infrastructure, and ultimately to the population. For example, a study of sand dune migration in northwest Kuwait (Al-Dabi *et al.*, 1997) demonstrated a sharp increase in the number and areal extent of sand dunes shortly after the war. In that study, multi-date Landsat TM images (1985, 1989, 1992, 1994) were used to map the temporal and spatial changes of Kuwait's major sand dune field, Al-Huwaimiliyah. This sand dune field is located in northwest Kuwait, and belongs to an active sand belt which has its source in southern Iraq (Figure 2). The sand belt is oriented along the prevailing wind direction and is the main source of prewar active sand in southern Kuwait.

Active sand or sand sheets are blanket-like deposits without slipfaces. Sand is transported from either nearby or distant source zones (> 100 km) along well-defined sand transport corridors, depending on wind energy. Kuwait lies within a high-energy wind environment (Fryberger *et al.*, 1979). Downwind, sand sheets usually show well-defined leading edges. These are especially visible on postwar TM images of Kuwait as shown in Figure 1b.

Figures 3a and 3b show a comparison of prewar and postwar TM images of an area in western Kuwait, to the southwest of the above-mentioned major dune field. The different atmospheric conditions at the time of data acquisition are reflected in the quality of the images. The prewar image is hazier and has a lower contrast than the postwar image. Nevertheless, a comparison shows that several features (indicated by arrows and circled area) which are visible on the prewar image are hidden on the postwar image by southeast-moving sand sheets.

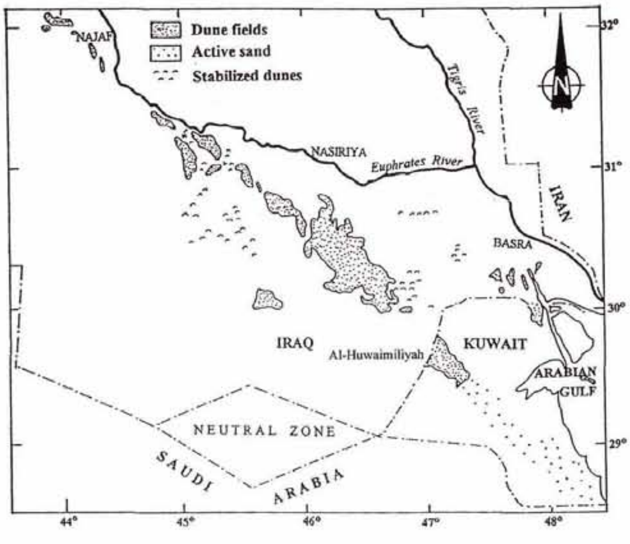
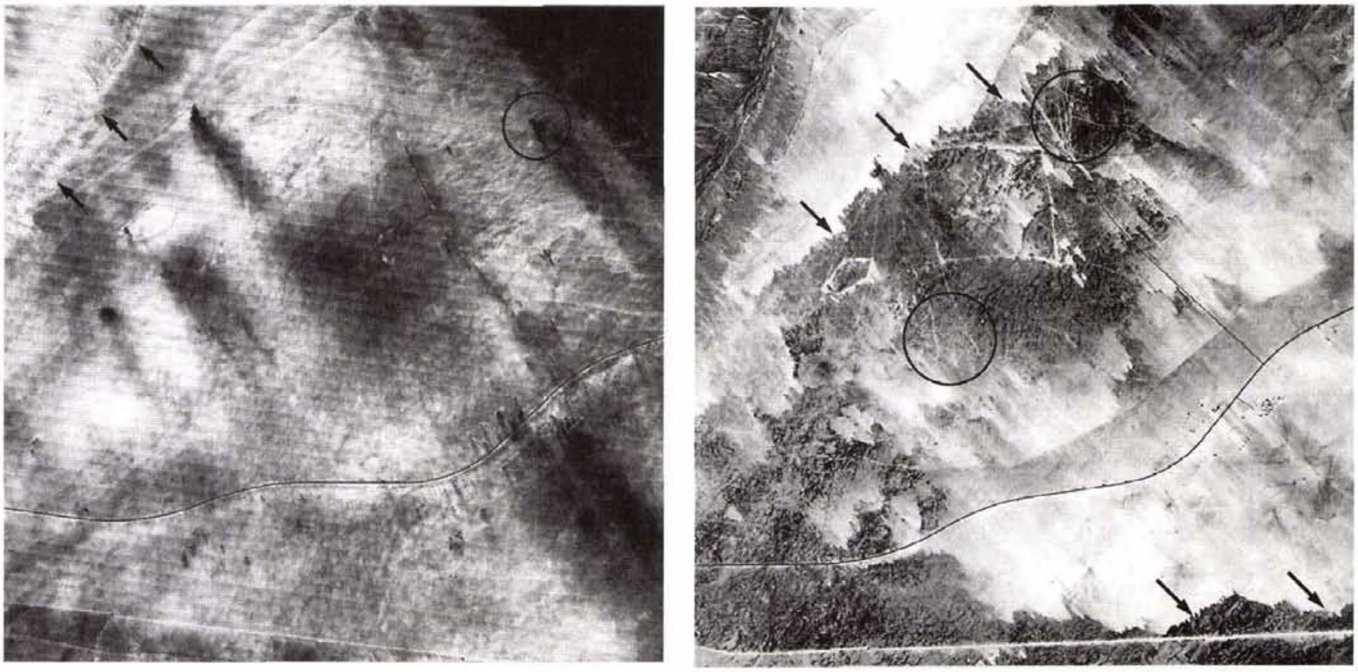


Figure 2. Distribution of sand dune fields and active sand belts in Kuwait and southern Iraq (modified from Skocek and Saadallah (1972)). Similarities in the textural and spatial characteristics of the dune sands south of Nasiriya in Iraq with those of northwest Kuwait confirm the relationship between both dune fields (Foda *et al.*, 1984).

Another distinct feature on the postwar image are numerous tracks produced by military vehicles (circled areas in Figure 3b). According to El-Baz (1994), the passage of military vehicles has caused disruption of the surfaces (desert pavement), exposing finer particles which are mobilized by the wind. The immediate effect is an increase in the amount of mobilized sand. War-disrupted surfaces therefore represent a supply source for sand sheets which augments the more distant source area in Iraq. The significance of this observation on the geomorphic development of the desert surface of Kuwait is discussed below.

In order to predict the impact of war-related hazards, it is necessary to construct accurate maps of the distribution and extent of surface change in relation to prewar surface conditions. Two map layers were prepared for statistical and spatial correlation. Categories corresponding to active and/or semi-active sand were grouped and extracted from the postwar classification map. Similarly, classes of the change-detection map were grouped into no/minor and major changes, and stored in separate raster files. The two maps (postwar spectral map and change map) were superimposed, and the active/semi-active sand category of the spectral class map was divided into no/minor change and war-disrupted areas, based on the degree of change recorded between 1989 and 1992. No/minor changed areas represent sand sheets that were active before the war and remained active after the war. War-disrupted areas have mobilized sand sheets resulting mainly from the disturbance of the desert surface by military activities. The correlation results show that 46 percent of the active sand category of the postwar classification map coincides with areas of no to minor change, and 54 percent coincides with major change areas of the change map. Mobilized or war-related active sand sheets are clearly distinguishable on the postwar images, because their high spectral reflectance contrasts strongly with the background (stabilized sandy or rocky surface) as shown in Figure 3b. The correlation results suggest an increase of more than 50 percent in the effects of eolian activity in Kuwait over a time period of three years.



(a) (b)

Figure 3. (a) Prewar Landsat TM image (31 May 1989, band 4) of western Kuwait showing the eastern escarpment of Wadi Al-Batin in the upper left corner (arrows). The escarpment as well as the circled feature have disappeared in Figure 3b because they have been covered by mobilized sand. Image covers an area of 54 by 54 km. See Figure 5 for location. (b) Postwar Landsat TM image (8 January 1992, band 4). Arrows point to edges of postwar sand sheet encroachment on the desert surface, while circled areas show desert surface disruption due to vehicle tracks. Image covers the same area as in (a). See Figure 5 for location.

Oil lakes were mapped into another GIS layer. Because of their small size, these features had to be mapped from high-resolution SPOT panchromatic images of 1992 (Koch and El-Baz, 1993). Using a GIS on-screen digitizing tool, oil lakes were delineated from contrast-stretched and edge-enhanced SPOT images. It was found that a piecewise stretch, emphasizing the part of the histogram related to the oil affected area, combined with an image minus Laplacian filter, gave the best results in sharpening the oil lake boundaries and, thus, facilitating their tracing. Figure 4 shows one example in the Burgan oil field. Numerous oil lakes (black spots) are recognizable within a generally darkened area of oil/soot deposits (tarcrete). An extensive network of new roads appears as bright lines within the area. These unpaved roads were built in order to provide access to the burning wells during fire-fighting operations, and constitute another form of surface disruption in addition to the pits and sand trenches that were dug out during the same activities (white dots in Figure 4).

The oil-contaminated areas represent an environmental problem related to the Gulf War. Rain water washes out chemicals from the oil contained in the tarcrete layer. This water infiltrates the soil and contaminates groundwater reservoirs (Al-Sulaimi *et al.*, 1993). Infiltration of oil in areas contaminated with oil lakes has changed the soil properties (Al-Sarawi *et al.*, 1997). Surface migration and leaching of oil from the oil lakes is also expected to have modified the topsoil structure, especially in the wadi fills and sabkha areas; this process may also result in increased runoff and erosion rates, and, consequently, to changes in the drainage pattern of the area.

Characterization of War-Affected Areas

To establish a relationship between prewar and postwar surface conditions, a map was produced showing areas demonstrating postwar surface changes (Figure 5). Two categories are considered here as major change features: war-disrupted areas (covering 17.2 percent of the country) and tarcrete (covering 4.4 percent of the country). The first category is derived by overlaying the active sand category of the spectral map on the major change category of the change map. Similarly, the tarcrete category was extracted by superposition of the oil polluted sand category of the spectral map on the major change category of the change map. Oil lakes constitute a third category (covering only 0.1 percent of the country, as of March 1992), but these are subject to change with time due to evaporation, infiltration, sand encroachment, and removal by pumping out the oil. Therefore, this category is not considered as a separate class in this map but included in the tarcrete category. The superposition and extraction procedures were performed at the scale of 1:100,000 used throughout this work. The derived map (Figure 5) delimits war-affected areas in Kuwait based entirely on computer classification of remotely sensed images and GIS analysis.

Using the map depicted in Figure 5 as a base, a coincidence analysis was conducted with the prewar surface sediment map (KISR, 1980). Each of the two surface-change categories (war-disrupted surfaces and tarcrete-covered areas) was used to mask the corresponding area on the surface sediment map, and a coincidence tabulation report was generated to identify the type and percentage of sediments that fall within each category. The results are shown as charts in Figure 6 and in tabular form in Table 2. Each category is expressed in terms of the corresponding surface sediments. The

Figure 4. Postwar SPOT panchromatic image (25 March 1992) of a section of the Burgan oil field showing the dark "tarcrete" from the oil well fires. Bright lines are roads that were built by fire-fighting crews, and black spots are oil lakes. Pits and sand trenches dug by fire-fighting crews appear as bright dots. Image covers an area of 10 by 10 km. See Figure 1b for location.

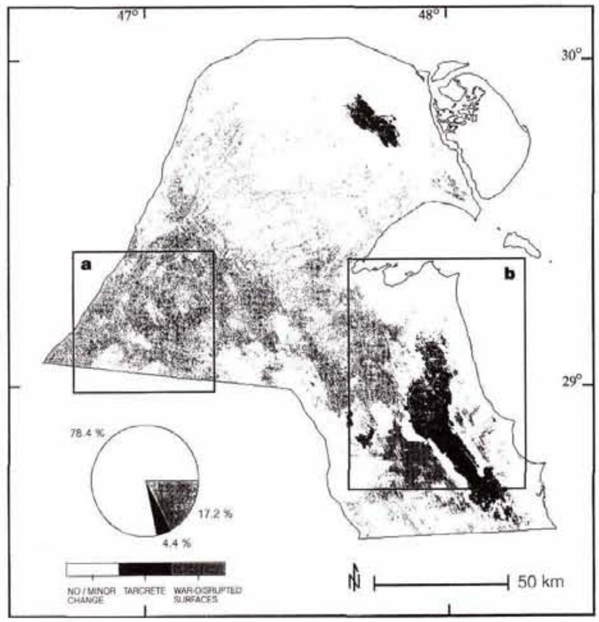


Figure 5. Map showing areas prone to postwar changes to the desert surface of Kuwait, particularly due to the mobilization of sand (17 percent), and the deposition of oil droplets and soot (4 percent). Box labeled **a** shows location of TM images shown in Figure 3, and box labeled **b** shows the TM images displayed as Figure 1.

distribution of war-disrupted areas (new mobilized sand) shows that 33 percent coincides with rugged (vegetated) sand, while 29 percent occurs on smooth sand, whereas tarcrete affects mainly the prewar smooth sand (45 percent) and active sand (23 percent). Other war-affected surface types are gravel ridges and gravel plains, and desert plains.

The main changes in surface sediment type and properties occurred to prewar (1) active, (2) rugged, and (3) smooth sand sheet deposits. According to Khalaf (1989), the first group consists of unprotected, well-sorted, and highly mobile sand. The second group is composed of immobile sand accumulations resulting from the coalescence of sand drifts around vegetation which acts as sand traps. The last group represents less mobile sand made up of a mixture of mobile sand and non-mobile granules. The development of sand sheet type is also related to topography. Rugged vegetated sand sheets occur mainly in shallow wide depressions, smooth sand sheets are usually characterized by relatively flat to slightly undulated surfaces, and active (mobile) sand sheets cover flat areas of Kuwait, and are associated with the occurrence of mobile sand dunes (which act as sand supply source) and prevailing wind direction (Khalaf *et al.*, 1984). Thus, of the war-disrupted surfaces, 33 percent occur on prewar rugged (vegetated) sand and 29 percent on smooth sand. Tarcrete is located mainly on prewar smooth sand (45 percent) and active sand (23 percent). The implication of these changes in surface dynamical properties are further analyzed in the next section.

Geomorphic Implications

The most striking observation obtained from comparison of prewar and postwar TM images, and supported by GIS analyses, is the considerable amount of sand that was mobilized between 1989 and 1992. The mobilization of vast amounts of sand in such a relatively short time is mainly the result of the damage to the desert surface caused by the Gulf War.

A comparison of the sand encroachment map (Al-Ajmi *et al.*, 1994) with the location of war-affected surfaces (Figure 7) shows that a significant area of war-disrupted surfaces falls outside the zone of severe sand encroachment as mapped before the war. The zone of prewar sand encroachment (zone A) coincides with the major wind corridor along the path of the sand supply in southern Iraq as noted above. The area to the south, zone B, represents a zone of mainly postwar sand encroachment. This zone was described on the original sand encroachment map as an area not subject to sand encroachment, and has been reclassified in this study as a postwar sand encroachment zone based on the results of the GIS analysis.

The changes in surface sediment type and distribution also affect the nature, magnitude, and geographical extent of

TABLE 2. COINCIDENCE TABULATION OF PREWAR SURFACE SEDIMENTS (ROW) AND POSTWAR SURFACE CHANGE (COLUMN). VALUES ARE IN PERCENT

	active sand	smooth sand	rugged sand	gravel plain	gravel ridges	talus scree	desert plain	playa	internal sabkha
war-disrupted surface	4	29	33	12	3	6	12	1	—
tarcrete	23	45	11	—	9	—	7	1	4

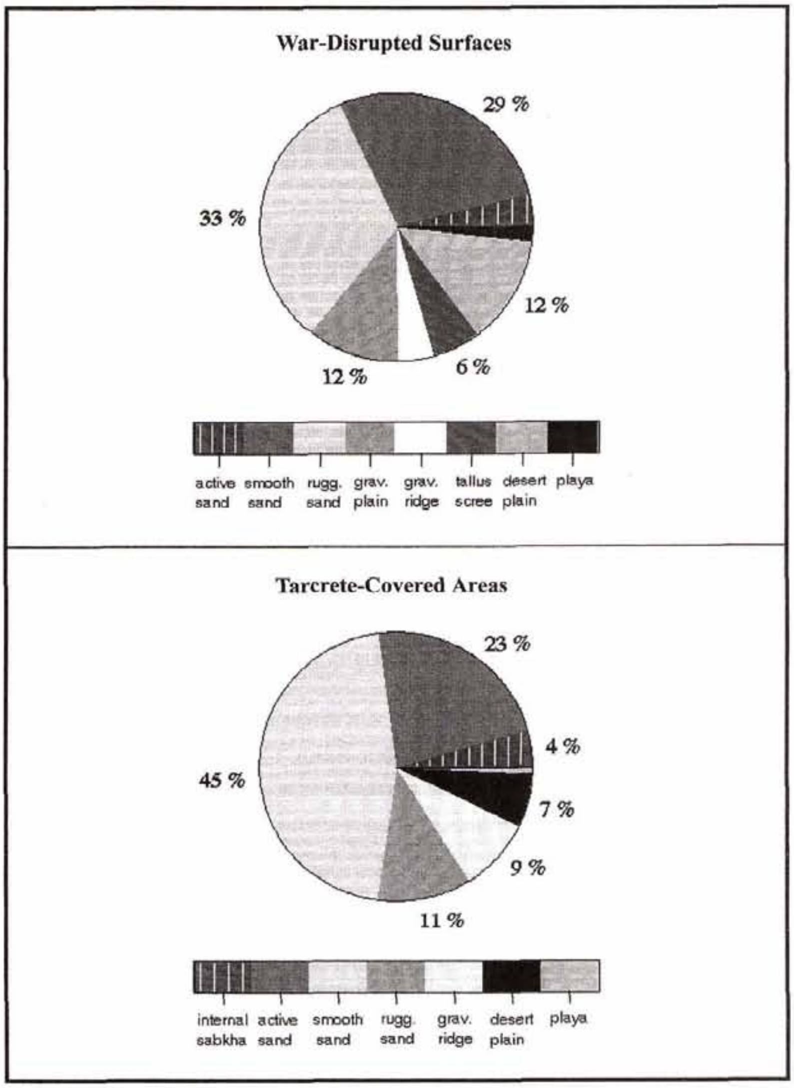


Figure 6. Results of coincidence tabulation of data from Figure 5 with prewar surface sediment map of Kuwait (KISR, 1980). The charts identify the type and percentage of sediments that fall in each category and the masking of the corresponding area on the surface sediment map.

geomorphic processes active in Kuwait, hence requiring existing description of the geomorphic provinces of Kuwait to be revised. According to Khalaf and Al-Ajmi (1993), there are nine geomorphic provinces in Kuwait: (1) coastal flat, (2) northern gravel, (3) southern sandy flat, (4) western calcrete flat, (5) Al-Huwaimiliyah undulated plain, (6) Jal Az-Zor escarpment, (7) Wadi Al-Batin, (8) major ridges, and (9) major depressions.

An overlay (Figure 8) of these nine geomorphic provinces and the surface change map of Figure 5 allows the visual identification of those provinces which have been subject to changes in surface characteristics. It reveals that the western and southern provinces (7 and 3) are the most severely affected by war-related changes in surface material, whereas the northern provinces (2, parts of 5, and 6) and the coastal province (1) are affected only to a minor extent.

Sand was mobilized in areas that were previously characterized by vegetated sand sheets as in the case of province (4) and the southern part of province (5). A consequence of this change in surface dynamics is that areas of rugged topography (due to vegetation acting as sand traps) may become smooth, and fixed dunes may become mobile. Province (3) is affected by a combination of mobilized sand and tarcrete that covers smooth to rugged sand deposits. Tarcrete occurs mainly in depressions overlying loose sand deposits and inland sabkhas.

In general, changes in surface characteristics and microtopography are the result of changes in the balance of geomorphic processes acting upon altered surfaces. In the desert surface of Kuwait, eolian processes are the main factors shaping the present land surface. These processes are controlled by the interaction of the nature of the exposed surface sediments, relief, vegetation cover, and wind regime. The removal of vegetation as well as desert pavement exposes finer particles which can be picked up by wind, increasing the load of sand or dust storms. Sand redeposition is currently occurring along the edges of the tarcrete-covered areas in the oil fields, such as the Burgan oil field (Figures 1b and 4). The

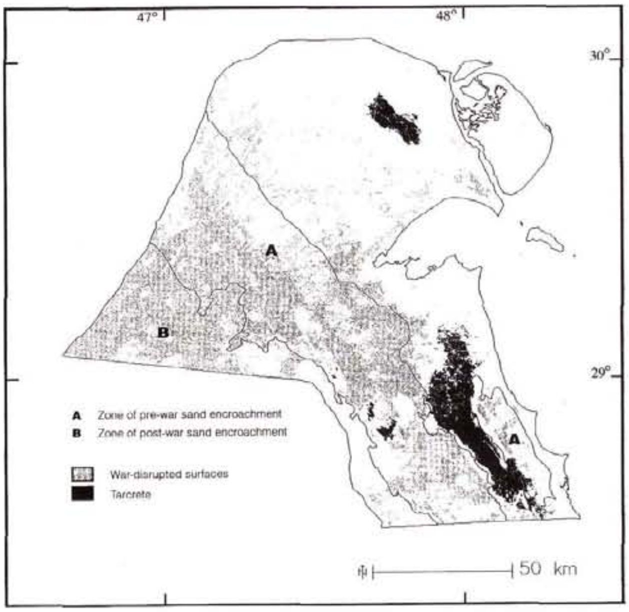


Figure 7. Map showing areas prone to severe prewar and postwar sand encroachment. Zone **A** lies within a major sand transport corridor supplying sand mainly from a distant source in Iraq, whereas zone **B** lies outside of this corridor. War-affected surfaces have modified the distribution of sand encroachment areas in Kuwait, suggesting an increased eolian activity in zone **A**, and a new sand encroachment area in zone **B**.

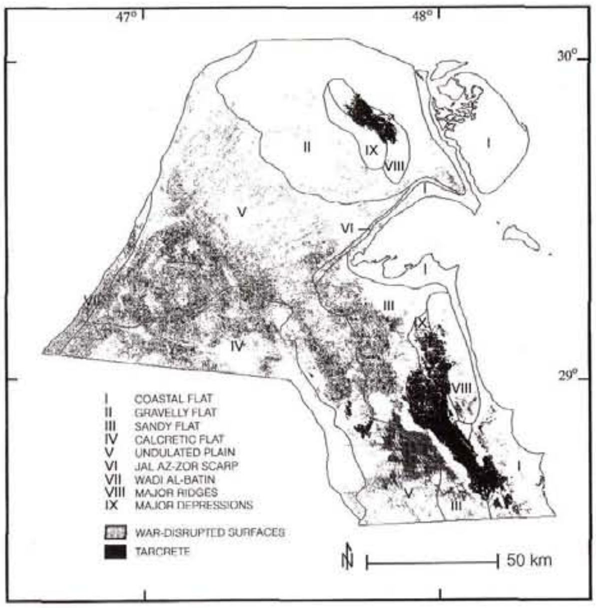


Figure 8. Postwar changes to the desert surface of Kuwait as they relate to the nine geomorphic provinces of Kuwait identified by Khalaf and Al-Ajmi (1993), showing areas that are subject to changes in surface dynamics.

tarcrete layer, which itself has changed the surface properties (El-Baz, 1994; Al-Sarawi *et al.*, 1997), is being covered by loose sand and will eventually disappear from the surface under sand sheets.

Conclusion

The relationship between prewar and postwar surface conditions in Kuwait's desert demonstrates the nature and extent of surface change and highlights some geomorphic implications. Information from satellite imagery used in conjunction with prewar map data allows the identification of the nature, extent, and geographic location of war-induced damage.

The resulting changes in surface dynamics will inevitably have an effect on landform patterns, such as roughening or smoothing of the surface, reactivating sand dune migration, and changing the drainage pattern. These changes have already had an effect on surface sediment properties, including changes in surface protection (desert pavement/vegetation), compaction, and pollution. A new map of geomorphic provinces is needed in order to account for these changes, but until the system returns to equilibrium, this map will only represent a transitional stage in land surface re-adjustment.

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