ASSESSMENT OF DAMAGE TO THE DESERT SURFACES OF KUWAIT DUE TO THE GULF WAR

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Abstract. This is a preliminary report on a joint research project by Boston University and the Kuwait Institute for Scientific Research that commenced in April 1992. The project aim is to establish the extent and nature of environmental damage to the desert surface and coastal zone of Kuwait due to the Gulf War and its aftermath.

Change detection image enhancement techniques were employed to enhance environmental change by comparison of Landsat Thematic Mapper images obtained before the wars and after the cessation of the oil and well fires. Higher resolution SPOT images were also utilized to evaluate the nature of the environmental damage to specific areas.

The most prominent changes were due to: (1) the deposition of a layer, up to 10 cm in thickness, of oil and course-grained soot on the desert surface in the lee of the wind as a result of "oil rain" from the plume that emanated from the oil well fires; (2) the formation of hundreds of oil lakes, which cover more than 30 square kilometers of the desert surface, from oil seepage at the damaged oil well heads; (3) the mobilization of sand and dust due to the disturbance of the natural "desert pavement" that protects the fine-grained soil beneath, which resulted in the formation of numerous sand streaks and dunes; and (4) the pollution of segments of the coastal zone by the deposition of oil from several oil spills.

Interpretation of satellite image data are checked in the field to confirm the observations, and to assess the nature of the damage. Final results will be utilized in establishing the needs for remedial action to counteract the harmful effects of the various types of damage to the environment of Kuwait.

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INTRODUCTION

Due to Iraq's invasion of Kuwait on 2 August 1990, the war preparations and the military conflict that ensued resulted in much degradation to the environment of the region. Environmental impacts resulted from the burning of Kuwait's oil wells, spilling of oil in the Arabian (Persian) Gulf water, and disturbing the desert surface by military activities. The latter was recognized by the senior author as a war-related environmental impact based on observations in the Sinai Desert of Egypt (Holden, 1991).

Severe environmental damage and disruption of operations in Kuwait's oil fields (Figure 1) resulted from the explosion of 732 wells by Iraqi troops before they left Kuwait. Efforts by 27 teams of fire fighters succeeded in capping the last well fire on 8 November 1991. This ended the dark plume of oil droplets, soot and smoke that emanated from the well fires, and ceased the "oil rain" that blackened vast stretches of the desert and polluted coastal areas of the
Gulf. The predominance of oil droplets in the "smoke plume" from the well fires was first noted by El-Baz (1992a and b).

As the well fires were put out, much oil seeped from wellheads and stagnated into pools. Furthermore, some of the wells exploded by Iraqi troops did not catch fire and continued to spew oil onto the land creating oil patches, streams and vast lakes (El-Baz, 1992c). These lakes hampered operations in the oil fields and constitute a health hazard to humans, animals and plants. Furthermore, roadbeds that had to be built to reach the oil wells during firefighting operations cause further hazards as they are affected by wind erosion and sand deposition. These features are clearly depicted in satellite images of Kuwait and neighboring regions.

SATELLITE IMAGES

Images obtained from various satellite systems have been utilized in the present study. For this reason, a description of the applicable systems is given below with emphasis on the data that pertain to the war's environmental impact; satellite images of the Gulf region obtained through June 1991 are listed by Williams et al. (1991).

1. Meteosat

Meteosat is a series of geostationary meteorological satellites launched by the European Space Agency (ESA); the first began operation in 1977. Two satellites are currently operating: Meteosat 3 is positioned at the Equator and 50 degrees west, above South America; and Meteosat 4 is positioned at the Equator and 0 degrees. Because the latter is positioned near the prime meridian, above West
Africa, the satellite's view of the Gulf is oblique, since it is located far from the nadir (Figure 2).

2. NOAA Satellites

The National Oceanic and Atmospheric Administration (NOAA) has two polar-orbiting Environmental Satellites. These are NOAA-10, which was launched in September 1986, and acquires data over the Gulf at approximately 7:30 am and 7:30 pm daily; and NOAA-11, which was launched in September 1988, and acquires data over the Gulf at approximately 1:40 am and 1:40 pm daily. Global Area Coverage (GAC), can be stored on a recorder. The latter is enough to cover an entire 102-minute orbit of data.

One of the uses of the NOAA Environmental Satellite images of the Gulf region is their ability to display the oil slick on the Gulf water. As these satellites have shown, the coastal zone of Kuwait and the Eastern Province of Saudi Arabia were affected by such slicks.

3. Landsat

Landsat satellites carry two instruments (Hord, 1986): a Multispectral Scanner System (MSS) and a Thematic Mapper (TM). The higher resolution images of the latter were used in this study, where the total area of Kuwait is covered by four TM scenes (Figure 3). Each intersection of a path and row number represents a center of a scene. Landsat scenes of Kuwait that were acquired between January and October 1991 show plumes emanating from the well fires (Figure 4).

Also, Landsat images clearly depicted the oil spills onto the water during the Gulf War. Prior to that war, the Gulf water and coastal zone had been altered by pollution from
oil spills at oil terminals and from tankers. From this point of view, the Arabian Gulf is one of the most environmentally fragile bodies of water in the world. Although it covers 233,000 km and is nearly 1,000 km long, it is a semi-closed basin. The only connection to the open water of the Gulf of Oman and the Arabian Sea is the Strait of Hormuz, which is only 86 km wide.

The Gulf water is characterized by weak counter-clockwise currents, high temperature and high salinity as compared to the water of the Gulf of Oman. This forces the water that exits through the Strait of Hormuz to do so near the bottom, while replacement water floats on top. These characteristics make it difficult to cleanse the Gulf water naturally, because the cycle of water exchange takes several years.

4. SPOT

The SPOT system was designed by the Centre National d’Etudes Spaciales (CNES) and built by the French industry in association with partners in Belgium and Sweden. Like the American Landsat it consists of remote sensing satellites and ground receiving stations. The imaging is accomplished by two High-Resolution Visible (HRV) instruments that operate in either a pancromatic (black-and-white) mode for observation over a broad spectrum, or a multi-spectral (color) mode for sensing in narrow spectral bands. The ground resolution are 10 and 20 m respectively.

The image area of each SPOT scene is approximately 60 by 60 km. Thus, it takes more scenes to cover the land area of Kuwait by SPOT images (13) than those of the Landsat TM images (4). All SPOT images acquired between January and October 1991 show the plume from the burning wells, but at slightly higher resolution.
5. Space Shuttle

Since 1981, Space Shuttle astronauts have taken photographs with the Hasselblad Model 500 EL/M and the Aero Linhof Technika 45 hand-held cameras. About 85% of these photographs are Earth-looking views. The rest show satellite deployments, extravehicular activities, and astronaut activities in the cabin (Williams et al., 1991).

Some of the photographs obtained by the Space Shuttle astronauts cover periods for which no Landsat or SPOT images were taken. These have proven very useful, particularly in displaying the effects of wind direction on the oil well fire plumes, as well as the spread of oil rain on the desert surface and oil lakes near damaged wellheads.

CHANGE DETECTION

Change detection is the process of identifying differences in the state of a surface or a phenomenon by observing it at different times. The basic premise in using satellite images for change detection is that changes in radiance due to land cover change must be large with respect to radiance changes caused by atmospheric and other factors. Several procedures of surface change detection using digital data have been proposed. These methods include comparison of land cover classifications, multivariate classification, image differencing/ratioing, principal component analysis, and change vector analysis (Singh, 1989).

Image Registration is the most important and the most tedious task in digital image processing. Registration is the process of transforming/warping one set of data (usually called the uncorrected image) to register it with a second set of data (usually called the corrected or master image). The
polynomial transform which describes how the uncorrected image data must be warped to fit over the master data is based on ground control points. After registration, the two image sets will have the same scale and rotation, and individual pixels will have exactly the same location in both scenes.

Landsat TM data obtained in January 1989 were utilized as the master images, and those obtained in June 1992 were considered uncorrected to test the utility of the technique in the study of changes in the oil fields of Kuwait. After image registration, the following steps are taken: (1) image regression to account for differences in the mean and variance between pixels of different dates due to changes in atmospheric conditions; (2) image ratioing to identify areas of change; (3) principle component analysis to reduce the number of components to principle changes; and (4) post-classification comparison to produce a change map.

In change detection techniques, spatially registered images of time t1 and t2 are subtracted, pixel by pixel, to produce a new image that represents the change between the two. The technique yields a difference distribution of each band, where pixels showing radiance change are usually found in the tail of the distribution, while pixels showing no radiance change tend to be grouped around the mean.

Using the software package EASI/PCI, a test was first conducted on a square area southeast of Kuwait International Airport. The site includes the southern town of Al-Ahmadi, the adjacent coastal strip, and a portion of the desert north and west of Al-Ahmadi. A portion of the Maqwa oil field is also included. The size of the image is 512 lines by 512 picture elements or pixels, which corresponds to approximately 15.36 km² on the ground. Eleven control points were selected for image registration.
The geometric registration resulted in a root mean square error of 0.12.

Three processes were examined for this site: regression, ratio, and subtraction. Due to extensive atmospheric haze, the 1992 image is very dark. It was thought that the regression analysis would be a preferred analytical tool because it would take into account the overall darkness of the 1992 image.

Band 4 of the 1989 image was subtracted from the 1992 image using PCI software. Figure 5 is the resulting image of the subtraction operation. Because most changes included a darkening of the desert surface, most types of change appear in darker tones while those areas or objects of little or no change are lighter.

A visual interpretation of the change image reveals oil lakes in the northwest corner, exploded oil tanks in the central portion, and darkened surface from oil rain in the western half of the image. The latter's trail follows the prevailing wind direction from the northwest to southeast. While this image is useful for interpretation, it does not provide quantitative assessments of change; each pixel must be interpreted and classified as change or no change according to its brightness value.

In order to determine boundaries or thresholds, a preliminary analysis of change at the pixel level was implemented. Twenty-seven sample pixels were selected within the image and covering the entire range of brightness values. The samples included areas of suspected change such as oil lakes, as well as areas thought to represent little or no change such as roads. The brightness values of each pixel were determined for the 1989, 1992,
and the change images. A histogram of the change image was also produced.

Analysis revealed that all but one pixel of change fell to the left of the mean of the entire change image, i.e., less than 117; brightness values of Landsat pixels vary from 0 to 255. The one pixel that was greater than 117 had a brightness value of 118. Therefore, the first threshold for change was set at 117 with values less than 117 indicating change. A second category of possible change was attempted based on the brightness values of pixels from a vegetated area. The assumption was that vegetation would not have been watered during the war, and would therefore, indicate change in the infrared from the 1989 to the 1992 image.

Healthy vegetation reflects strongly in the infrared. Lack of water would destroy some of the vegetation, resulting in a decrease in the infrared reflectance. Based on this information, a second threshold of possible change was selected at 145. Thus, the first analysis resulted in three divisions of brightness values: 0-117 (change), 118-144 (possible change), and 145-255 (no change).

In order to determine a more appropriate threshold for the possible change segment, an additional 20 sample pixels were selected from within the town of Al-Ahmadi based on the assumption that the town itself experienced little change. Pixels were selected from areas between the roads, and the three brightness values were calculated for each of these new pixels. A new threshold was set at 122, based on the brightness values of the change image, resulting in establishing the possible change range at 118-122.

The change segment needed further refinement to identify oil lakes as a distinct segment. Additional pixels were
selected from those areas suspected to be oil lakes as seen on the 1992 and change image. Analysis of the change brightness of the suspected oil lakes resulted in new segments with the ranges of 0-90; and 91-117. Based on the above data, the following four categories were established for this site: 0-90 (oil lakes), 91-117 (deposit of oil rain), 118-122 (possible other changes), and 123-255 (no changes).

These results prove beyond doubt the utility of change detection techniques in qualitatively and quantitatively establishing the extent, and possibly the nature, of environmental change in the oil fields of Kuwait due to the Gulf War utilizing the Landsat Thematic Mapper data.

GIS CORRELATIONS

For the assessment of environmental damage, Geographic Information System (GIS) methodologies are utilized in the correlation of remotely sensed information with other sources of data. GIS technology is used to provide a computer-based method of storing, retrieving, analyzing, and displaying spacially organized data. An operational GIS consists of computer hardware and software that allow use of data layers from a variety of sources. Such data include digitized aerial photographs, topographic maps, land use and road maps, satellite images, and field observations.

GIS software is used to provide a capability to: (1) store data in the most easily retrievable form; (2) update the data in a timely manner; (3) overlay various data sets for easy correlation and analysis; (4) derive new information from existing data, which may include slight changes in the condition of the environment. Such an arrangement of data in a GIS assisted in manipulating the information for the
specific needs of assessing the damage to desert surface of Kuwait due to the Gulf War, with particular emphasis on the mapping of oil lakes.

A set of oil lakes maps, produced by the Kuwait Institute for Scientific Research (KISR), were digitized and installed into a GIS database to facilitate further data manipulation. The manipulations consist, for example, of overlaying oil lakes maps on other map layers or satellite images to show the respective spatial distribution of oil lakes, and calculate number, shape, and size of lakes in each map layer. In order to perform this type of analysis, first analog map information were converted to a digital format, and then incorporated into a GIS. This process consisted of four parts: 1) map preparation, 2) manual digitizing, 3) installation of map information into a GIS, and 4) data analysis.

Photocopies of six oil lakes maps were obtained from KISR, at an approximate scale of 1:50,000, which cover five oil fields: Rawdhatain, Sabriya, Maqwa, Ahmadi, and Burgan. All oil lakes were redrafted onto a clear sheet (mylar) and referenced according to a UTM grid system. Wherever possible, an original topographic map (scale 1:50,000) was used as a base map to establish the exact position of each oil lake. This was necessary because photocopies generally show some radial distortion. The oil lakes belonging to the southern three oil fields (Magwa, Ahmadi and Burgan) were manually corrected on original 1:50,000 base maps.

A digitizing software package, ROOTS, was employed to convert the oil lakes maps into a digital format. First, control points were marked on a clear mylar sheet and their respective UTM coordinates were annotated to ensure that multiple map sheets of the same or adjacent areas utilize the
same coordinate system. Then, the contour of each oil lake was traced with a digitizing devise and labeled with the corresponding category code. Finally, the digitized map was checked and edited for any errors.

The utilized GIS software is GRASS 4, which is especially suitable for spatial manipulation of data in raster format. Before bringing a digitized map into GRASS, certain decisions had to be made with respect to how detailed should each map layer be (spatial resolution), how many category types should be depicted (data classification), and within which regional boundaries (geographic location) should the map layers appear, so that maps from one mapset can later be combined with maps of another mapset.

Specifically, GRASS asks for the UTM zone, UTM coordinates outlining the map area (easting and northing), and the cell size in meters. A cell size of 30 m was chosen since this represents 0.6 mm on a 1:50,000 map, and is equivalent to the accuracy with which the maps were digitized. Another reason for choosing this cell size is that TM images have the same spatial resolution, which is important when merging map data with TM images.

After bringing a map from ROOTS into GRASS, the map is converted from its vector format to a raster format. Each oil map was then be displayed separately (Figure 14), or, as in the case of the adjacent oil fields Maqwa, Ahmadi and Burgan, they can be combined to one raster file. A vector file, showing the main roads, was overlain on the oil field maps to better indicate the geographic location of each individual oil lake (Figure 6).

Since both map layers were digitized from two different maps at different scales, the oil lakes are slightly misplaced with respect to the road network. This is a common
problem when using map data derived from different sources, and must be remedied before combining both maps for data analysis. However, for calculating the aerial extent of oil lakes, no additional spatial corrections were required. This is due to the fact that these data were checked with TM images, and their accuracy allows precise mapping of the oil lakes of Kuwait.

The oil lakes are also clearly depicted in SPOT data, even in areas where the land had been darkened by a thick coat of oil rain. Figure 15 shows the case of Raudhatain field in northern Kuwait where elongated oil lakes abound along the western border of the blackened earth, and sand-filled pits dug around wellheads during the firefighting of the oil well fires appear as bright squares in the darkened earth zone.

CONCLUSION

Satellite images are most useful in the detection of environmental change due to the Gulf War. These images depicted the effects on the atmosphere plumes from the burning of Kuwait's oil wells, on the Gulf water from numerous oil spills, and on the land surface from severe disruption of the desert surface.

The most applicable use of digital images from Landsat satellites is the utilization of change detection techniques. Change maps resulting from such applications could easily be utilized into a GIS to produce thematic maps, compare with results of field observations, and/or generate environmental change maps.

It is recommended that available satellite images particularly those of Landsat and SPOT taken before and after the Gulf War are studied utilizing the aforementioned
methods and techniques. This would allow the collection of basic scientific data and its organization in a user-friendly environment. This, in turn, would allow easy access to such data for the evaluation of what needs to be done to alleviate the environmental problems that resulted from the GULF WAR.

REFERENCES


Figure 1. Map of Kuwait showing its major geographic features and the location of ten oil fields.
Figure 2. Meteosat image acquired on 10 February 1991, showing smoke plumes from Kuwait oil well fires just west of the Arabian Gulf.
Figure 3. Schematic illustration of the area coverage of Kuwait by four Landsat Thematic Mapper Images.
Figure 4. Smoke plumes from burning wells of the southern oil fields of Kuwait as depicted in a subscene of a Landsat Thematic Mapper image acquired on 15 February 1991.
Figure 5. Change detection image produced by square root enhancement of Landsat Thematic Mapper image using band 4 (infrared; 0.79-0.9 microns) where dark pixels indicate change in the Ahmadi Oil Field of southern Kuwait.
Figure 6. Map of the oil lakes in the Magwa, Ahmadi and Burgan Oil Fields as mapped from SPOT images acquired on 25 March 1992 with the main road network added utilizing GIS methodologies.