DESERT S.H.I.E.L.D.

Satellites Helping the assessment of gulf war-Inflicted EnvironmentaL Damage

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ABSTRACT - *Both during and after the Second Persian Gulf war of 1990-1 the desert and marine environment were threatened by the effects of warfare. Coalition forces and Iraqi forces alike were detrimental to the environments of Kuwait in particular and the Persian Gulf region as a whole. Oil wells were set on fire and oil pipeline valves were opened, polluting both the Kuwaiti desert and the Persian Gulf. The preparations for the war and warfare itself disturbed the desert surface, resulting in erosion, mud floods and sandstorms.*

The environmental damage considered here was very exceptional in that it occurred in a war-zone. This hindered the routine use of reconnaissance aircraft and field surveys. Satellite remote sensing data thus became an important source of information in aiding the assessment and evaluation of the environmental damage. These data were also used as input for computer models predicting the movement of oil slick and smoke plumes and afterwards as verification material for the computer output. Already during the aftermath of the Second Gulf War remote sensing data were available to scientists and environmentalists.

This paper gives an insight into the various ways in which satellite remote sensing data were helpful to the rapid detection, assessment and evaluation of the environmental threats in order to keep the ecological impact to a minimum.

1. ECOLOGICAL WARFARE

1.1. Oil well fires

At the time of the Iraqi invasion of Kuwait on 2 August 1990, some 900 wells were capable of oil production (F. El-Baz, 1992, p.72). During the aftermath of the ground war the Iraqi's as they retreated, demolished about 800 oil wells, carrying out Saddam's long-threatened retaliation against Kuwait's oil-producing infrastructure. Of these wells 656 were ablaze for several months until the last remaining oil well fire was extinguished on 6 November 1991 (A.R. de Souza, 1991, p.17). The other 74 wells gushed oil forming lakes and pools (T. Husain, 1994, p.2150). This ecological disaster not only threatened human health, but affected the Gulf marine and desert flora and fauna as well.

Smoke emanating from the burning oil wells consisted of numerous chemicals, various gases, huge amounts of carbon particles and crude oil droplets. Most of the smoke plumes have been restricted to the lower atmosphere up to 3 kilometres within a range of about 1,000 kilometres around Kuwait (S.W. Dech & R. Glaser, 1992, p.3248; A.R. de Souza, 1991, p.18-19; G. Stephens & M. Matson, 1993, p.1427), covering an area of 15-30,000 km² (F. El-Baz & R.M. Makharita, 1994, p.116). Thin smoke veils were even detected at an altitude of 6 to 7 kilometres nearly 2,000 kilometres east of Kuwait in southwestern Pakistan (S.S. Lamaye *et al.* , 1991, p.1536). Black snow was observed as far away as Kashmir, India, 2,600 kilometres east of Kuwait (A.R. de Souza, 1991, p.19).

The smoke partially prevented the sunlight from reaching the Earth's surface during the day, causing a cooling effect (A.R. de Souza, 1991, p.19). Soot fall out had a strong impact on the vegetation in the Gulf region as it darkened the desert surface, reducing photosynthesis. Plants were coated with oil or soot, affecting their growth. (A.R. de Souza, 1991, p.15). It was estimated that the black oily rain doubled the amount of oil spilled directly into the Gulf (http://umbc7.umbc.edu/˜tbenja1/baumann1/baumann1.html). Black rain precipitated as far south as Qatar (A.R. de Souza, 1991, p.19).

Detonated oil wells which did not catch fire flowed uncontrollably forming stagnant pools of oil several kilometres long and more than a meter deep with an estimated total volume of 25 to 50 million barrels (1 barrel = 35 gallons), endangering the potability of the alluvial groundwater reserves (A. R. de Souza, 1991, p.11).

1.2. Oil spills

On January 21, two days after the Coalition forces launched their air campaign against Iraq, Iraqi forces deliberately opened valves at Sea Island, an offshore oil transhipment terminal, and offloaded crude oil from moored tankers, creating a huge oil spill in the Gulf (http://umbc7.umbc.edu/˜tbenja1/baumann1/baumann1.html; A.R. de Souza, 1991, p.16). This oil slick was for the first time detected by AVHRR imagery, 60 kilometres south of Sea Island on 23 January 1991.

Not only the Iraqi's were guilty of the oil spills. The bomb raids of the Coalition airforces caused the release of oil into the Persian Gulf as well (A.R. de Souza, 1991, p.16). Until at least late May 1991 oil continued to be discharged into the Persian Gulf (http://umbc7.umbc.edu/˜tbenja1/baumann1/baumann1.html).Estimates of the size of the oil spills range from 24 to 600 million gallons of oil (F. El-Baz, 1992, p.74). Oily sediments were to be found not only on the Gulf's water surface, but also on the seafloor and along its shores, endangering the fragile Gulf ecology and the inlets of desalination plants.

Unfortunately the natural cleansing of the Persian Gulf, which covers 233,000 square kilometres and is nearly 1,000 kilometres long (F. El-Baz, 1992, p.73), will take a very long time, due to its low exchange rate. Water comes in from the Shatt-al-Arab: the confluence of the Eufrates and Tigris rivers just before they flow into the Gulf . The Stait of Hormuz, which is only 86 kilometres wide, is the only connection to the open water of the Gulf of Oman and the Arabian Sea.

1.3. Disruption of desert soil

The upper layer of the desert surface consists of pebbles, which act as an armour protecting the finer particles beneath it from the erosive action of the wind and water (F. El-Baz, 1992, p.74). The digging of trenches and foxholes and the building of berms and walls of sand resulted in the exposure of vast amounts of soils to fluvial and eolian erosion, providing source material for dust particles and dune sands. Sandstorms may also further spread soot and oil throughout the region.

Not only during the onset of the ground war the desert surface was disturbed, but also resulting from warfare: the movement of thousands of military vehicles and the dropping of high explosives (A.R. de Souza, 1991, p.5). This paper does not further treat this source of environmental damage, but focuses on the assessment of environmental damage resulting from the oil fires and oil spills.

2. REMOTE SENSING THE GULF REGION

As the oil smoke plumes and oil spills not only harmed the environment, but also posed a threat to the provision of fresh air, to the desalination plants along the coasts of the Persian Gulf, which provide the population with potable water (http://umbc7.umbc.edu/~tbenja1/baumann1/baumann1.html), and to the alluvial ground water deposits through the percolation of oil droplets from the desert oil lakes (A.R. de Souza, 1991, p.15), it became very important to detect the environmental damage as soon as possible and to monitor it very accurately and continuously.

2.1. Earth observation satellites

Due to warfare no conventional aerial or ground surveys could be undertaken to acquire data on this ecological disaster. Therefore satellite remote sensing data was used to locate the fires themselves and to study the extent of the smoke, its movement and dispersion and to assess the location, magnitude and spreading of the oil spills. Earth observation satellites, such as Landsat and Spot, do not acquire images as frequently as meteorological satellites. Their advantage lies in the fact that they have a higher spatial resolution..

2.1.1. *Landsat*

The satellites currently operated by the United States National Aeronautical Space Administration are Landsat 4 and 5. These earth observation satellites cross the Equator at approximately 09:45 am. They carry two instruments: the Multispectral Scanning System (MSS) and the Thematic Mapper (TM). The spatial resolutions of these instruments are 80 m and 30 m respectively. The thermal infrared sensors of the TM have a spatial resolution of 120 m. The total area of Kuwait is covered by four TM scenes of approximately 185km $\times$ 177 km (F. El-Baz & R.M. Makharita, 1994, p.7).

Landsat scenes acquired over Kuwait between January and October 1991 show very distinctly the oil smoke plumes. The location and number of burning wells were estimated through the study of the thermal infra-red band (band 6) of the Landsat Thematic Mapper (F. El-Baz, 1992, p.72). A comparison of this band with band 7 reveals the fires even through thick smoke. Colour composites generated from band 4, 5 and 6 were used in mapping the fire sources and the smoke plumes as well (T. Husain, 1994, p.2151).

TM band	spectral resolution (µm)
4	0.76-0.90
5	1.55-1.75
6	10.4-11.7
7	2.08-3.35

Table A. Spectral resolutions of TM bands (source: E. C. Barret & L. F. Curtis, 1992, p.86)

Landsat Thematic Mapper data are also useful for monitoring spilled oil as will be discussed in the following paragraph. To predict the environmental impact on the Gulf ecology, Landsat TM data can be used as well to estimate sea water depths and identify vegetation types (A.R. de Souza, 1991, p.16).

2.1.2. *Système Pour l'Observation de la Terre (SPOT)*

In January 1990 SPOT-2 was launched by a consortium of European nations led by the French space agency, Centre National d'Etudes Spatiales. This sun-synchronous near polar orbiting satellite has an equatorial crossing time of 10:30 am mean local solar time. Its revisiting time is 26 days. The provision of off-nadir viewing (through the two High Resolution Visible imaging instruments) made it possible to acquire stereoscopic photographs to determine the height of smoke plumes (S.S. Lamaye *et al.* , 1991, p.1536) and to reduce the revisiting time as to monitor the Gulf region every four days at a spatial resolution of 10 or 20 m, depending on the mode of observation (panchromatic or multi-spectral respectively). Individual oil fires are shown clearly on Spot imagery (A.R. de Souza, 1991, p.18). The total land area of Kuwait is covered by 13 SPOT images of approximately 60 by 60 kilometres.

2.2. Meteorological satellites

Meteorological satellites on the other hand observe large areas at a relatively low spatial resolution, but they obtain images more frequently than the observation satellites mentioned above. Their high repetitive rate makes these satellites highly useful for an almost continuous monitoring of dynamic processes like the spreading of oil spills and the diffusion of smoke plumes (T. Hussain, 1994, p.2151).

2.2.1. *National Oceanic and Atmospheric Administration*

The NOAA-10 and NOAA-11 are polar orbiting environmental satellites (POES). The first satellite acquires data over the Gulf at 7:30 am and 7:30 pm daily, the other one at approximately 1:30 am and 1:30 pm (F. El-Baz & R. M. Makharita, 1994, p.4). This results in four scenes per day provided by NOAA's National Environmental Satellite, Data and Information Service (NESDIS). The satellite data can be recorded in 1.1 kilometre spatial resolution (Local Area Coverage) or 4 kilometre resolution (Global Area Coverage). One of the uses of these satellites is their ability to display the oil slick in the Gulf water. Images show smoke plumes very distinctly as well. (A.R. de Souza, 1991, p.16). Besides the TOVS, the TIROS Operational Vertical Sounder, the other primary sensor of the NOAA-satellites is the AVHRR. The Advanced Very High Resolution Radiometer contains 4 or 5 different bands aboard the NOAA-10 and NOAA-11 respectively, covering the visible, near-infrared and thermal infrared parts of the electromagnetic spectrum (F. El-Baz & R.M. Makharita, 1994, p.4).

band[1]	spectral resolution (µm)
1	0.55-0.68
2	0.725-1.1
3	3.53-3.93
4	10.3-11.3
5	11.5-12.5

Table B. Spectral resolutions of AVHRR-bands (source: G. Stephens & M. Matson, 1993, p.1424-5)

Apart from Landsat TM data (*as mentioned before*) colour composites of bands 3, 4 and 5 of the NOAA-AVHRR sensor were also used to locate the burning oil wells and to assess the areal coverage of the smoke plumes (T. Husain, 1994, p.2151). To distinguish between the oil fires and the desert background the thermal band 3 was used . This band is able to detect "hot spots", sub-resolution scale high temperature sources (T. Husain, 1994, p.2149; N. Khazeni & K. A. Richardson, 1993, p.1271; G. Stephens & M. Matson, 1993, p.1425). These hot spots can best be noticed on night time images, when temperature differences between the heat source and background are maximum. Since the height to which smoke can rise depends on the strength of the heat source, NOAA-AVHRR data of band 3 was also helpful to determine the height of the plumes (S.S. Lamaye *et al.* , 1991, p.1537). In the next paragraph will be discussed how NOAA-AVHRR data was used to detect even thin smoke veils over the Persian Gulf.

Landsat (*see next paragraph*) and NOAA satellite data have proved very effective in the detection of oil spills (A. M. Cross, 1992, p.782). Slick detection using data of the thermal infrared bands has always been more problematic. In this situation it has been relatively easy, probably due to the early detection of the oil spills within the

[1] The AVHRR-sensor aboard the afternoon satellite acquires data in 5 bands, the morning satellite in 4 bands.

first few days of the initial release, whilst the mixing of oil and water within the slick region was limited. In the AVHRR imagery it was sometimes possible to discriminate anomalously warm areas in the waters of the Gulf, especially during the day (G. Stephens & M. Matson, 1993, p.1427; A.M. Cross, 1992, p.784; F. El-Baz,1994, p.5). These were expected to be due to oil slicks from leaking tanker loading facilities (G. Stephens & M. Matson, 1993, p.1427). This was later affirmed by overlaying these images in a GIS with the digitized courses of oil pipelines and terminal facilities (A. M. Cross, 1992, p.784).

2.2.2. *METEOSAT*

METEOSAT-4, launched by the European Space Agency (ESA), is positioned at the Equator near the prime meridian resulting in a far from nadir oblique view of the Gulf region. This geostationary weather satellite produces nearly continuous coverage with acquisitions every half an hour albeit at a lower spatial resolution than earth observation satellites.

METEOSAT imagery was very useful in monitoring the shape, speed and movement of the plumes (F. El-Baz, 1992, p.72). Coupling the monitoring of the movement of the smoke with the knowledge of winds from weather forecast models provides another estimate of the heights to which smoke has risen (S.S. Limaye *et al*., 1991, p.1537). Due to its altitude of 35,900 kilometres (E.C. Barrett & L.F. Curtis, 1992, p.95), METEOSAT-4 imagery covers a large area. It was therefore able to follow the smoke veils as far away from Kuwait as into Turkey and Pakistan (S.S. Lamaye *et al*. ,1991, p.1537; A.R. de Souza, 1991, p.18).

3. APPLICATIONS

3.1. Assessment of the areal extent of oil spills using Landsat TM imagery[1]

In order to rapidly determine where to concentrate resources to combat the oil spills in the Persian Gulf, Landsat Thematic Mapper data was analysed, merely using simple mathematical operations. This restriction was made because if such disasters will happen in other developing countries as well, where little expertise on remote sensing is available, personnel has to be trained very quickly.

Data of TM's mid-infrared bands (5 and 7) were used to separate the oil's strong reflectance from the low reflectance values associated with the water. Especially band 5 showed areas with higher reflectance values than normal water. To make full use of the absolute data range and to obtain more detailed images each band was stretched. After classifying the image using density-slicing techniques, the areal extent of oil spills could be measured by counting the pixels classified as containing oil and multiplying them by their spatial resolution (30 × 30 m).

Surface class	Value range	Numberof pixels	km^2	Value range	Number of pixels	km^2
Water	1-30	150,830	135.74	1-24	143,499	129.14
Light Oil	31-69	21,013	18.91	25-39	l 7,188	6.46
Heavy Oil	70-80	17,238	15.51	40-39	l 6,546	5.89
Land	81-250	70,980	63.88	54-250	104,911	94.41

Table C. Density slicing before (left) and after (right) rectification for oil surfaces over land

Nevertheless, oil surfaces over land were misclassified as being oil surfaces over water areas due to the fact that both classes had the same reflectance values in band 5. This led to an overestimation of oil spills in the Gulf water.

To distinguish between these two classes band 4, which was very helpful in distinguishing between land and water, was added to form a new image. This image was classified once more (based on new value-slices, because of the merging of band 4 and 5) to determine the actual extent of the oil spill in the Persian Gulf. Looking at table 3 one notices indeed a reduction of the areal coverage of oil and an increase in the areal coverage of land when comparing the values left and right of the bolded line.

3.2. Assessing thin smoke veils over the Persian Gulf with AVHRR data[2]

Using conventional methods smoke is due to its optical thinness very difficult to distinguish over water on many environmental satellite images , since it reflects, like the underlying sea surface so little solar radiation. Its detec-

[1] This section is for the most part based on the lesson module downloaded from the internet page: *http://umbc7.umbc.edu/˜tbenja1/baumann1/baumann1.html*

[2] This section is for the most part based on: *N. Khazenie & K.A. Richardson (1993). Detection of oil fire smoke over water in the Persian Gulf Region. Photogrammetric Engineering & Remote Sensing, 1993, 59 (8). pp 1271-1276.*

tion is furthermore frustrated since the optical thickness varies along its course. Therefore the plumes are only detectable when the smoke is of a relatively high concentration. Just the heavy smoke plumes are visible on all remote-sensing images acquired (A.R. de Souza, 1991, p.8).

To facilitate the detection of more than just the obvious smoke plume over water bispectral composites of AVHRR images were constructed. The composites are a ratio between channel 1 and 2. Although neither image by itself depicted any smoke over water, the composite imagery contained enough information to extract the signature. As the ratio varied significantly over land, traditional enhancement techniques (like the stretching technique mentioned before) were not proficient. It took too much computing time and human input.

A more sophisticated approach was selected: texture analysis. These methods characterize local spectral variations in an image. The family of Gabor transformations proved to be the most efficient and robust automatic spatial textural feature discrimination method. These filters discriminate textural features similar to human vision. This detection method can be performed quickly and without expertise, allowing analysts to produce useful imagery within in a short period of time. This is very useful in emergency situations, where users are under pressure to analyze imagery in real time.

4. CONCLUSIONS AND SUMMARY

The environmental damage due to the Second Persian Gulf war is unprecedented in its scale and diversity. Lacking data from conventional surveys, satellite remote sensing data was the only source available for a very long time until hostilities terminated. Four different platforms were available at that time: Landsat, Spot, NOAA and METEOSAT. With regard to the assessment of environmental damage they all had certain abilities in common or had a very distinct application.

In the last paragraph two specific applications are discussed more laboriously. These are very valuable in that they provide us with easy to master techniques which generate information very quickly. Especially in developing countries where there is a lack of human capital with regard to remote sensing and in cases of ecological disaster these characteristics can be taken full advantage of.

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