UNIVERSITY OF SOUTHAMPTON

CREATION OF A COASTAL ZONE INFORMATION SYSTEM FOR QATAR USING REMOTE SENSING AND GIS

by

Ali Abdulla Qassim Khamis Al-Hargan

Thesis submitted for the
Degree of Doctor of Philosophy

Centre for Environmental Sciences
Faculty of Science

September 1997

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UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF SCIENCE

CENTRE FOR ENVIRONMENTAL SCIENCES

Doctor of Philosophy

CREATION OF A COASTAL ZONE INFORMATION SYSTEM FOR QATAR USING REMOTE SENSING AND GIS

by Ali Abdulla Qassim Khamis Al-Hargan

Oil spills in the Arabian Gulf are a major and continuous threat to the fragile and vulnerable coastal zones of the region, especially the coastal zone of northern Qatar which lies almost in the middle of the Gulf's water. This situation makes the northern half of Qatar peninsula vulnerable to any oil spills that might occur in the Gulf which are influenced by the counter-clockwise currents system in the Arabian Gulf.

The aim of this thesis is to establish an ESI information system for the northern Qatar coastal zone using remote sensing and GIS technologies. Environmental Sensitivity Index (ESI) mapping is a classification and ranking of the relative sensitivities of various geologic, geomorphic and biologic coastal environment types on a scale of 1 to 10 in terms of indicating the persistence of oil and potential for biological habitat damage. ESI mapping is usually associated with oil spills response and contingency planning, because it provides a tool to assist spill-response coordinators and government agencies in planning or operating strategies for protection and spill management.

Remote sensing has great potential for application to the complex environmental problems of the coastal zone. Its potential is derived from the spatial, spectral and temporal digital data provided by the system, which can be used for physical and ecological studies of the coastal zone and marine environments. Remotely-sensed data can be combined with other spatial data in a GIS system for effective management of the coastal zone, though this has not often been achieved at operational level for various technical and logistical reasons which are discussed in the thesis.

Applying remote sensing and GIS to enhance the traditional approach of ESI mapping involves the processing of high spatial resolution airborne MEIS (Multi-detector Electro-optical Imaging Scanner) data (2 m spatial resolution) for the whole coastal zone of Qatar. This provides the missing information on the coastal zone vegetated habitats which are essential in the ESI mapping. Manipulating the compiled ESI information in the GIS system to overcome the difficulties of assembling the necessary materials of ESI in hardcopy form, handling it through manual techniques, and the difficulty of applying consistent procedures within such an approach are further challenges that have been tackled.

Several types of image processing techniques were applied to the MEIS data in order to find the best analysis to handle the large volume of digital data and at the same time reveal the information needed in the coastal zone for the ESI mapping. These techniques range from conventional classification and resampling to newer techniques of image compression, and automated spectral pixel unmixing analysis. Image compression and automated spectral pixel unmixing are found to be well suited to handle the large volume of digital data and reveal the information needed in the coastal zone for the ESI mapping. Better results would be achieved if the original MEIS flight lines data had not been mosaicked to form rectangular blocks of MEIS data. Detailed mapping of the very sensitive coastal resources in northern Qatar is achieved using visual interpretation of JPEG compressed digital images and a spectral library of surface materials is built for use in spectral pixel unmixing.

Finally an ESI has been created for the northern Qatar coastal zone using the information yielded from the remotely sensed data and conventional surveys. The ranking of the coastal zone sensitivity types was based on known interaction of oil with various coastal types which have been observed over the past years. A GIS ESI map has been created for northern Qatar to illustrate all the information needed by the personnel in charge of the cleanup operations. The GIS ESI map highlights the most sensitive sections of the coastal zone to show the areas at risk during oil spills thus would need the most protection. The GIS allows the management decisions on oil spill to be made in real time. ESI can be used not only for oil spill response planning, but also for the establishment of a coastal zone management plan which will be highly beneficial for Qatar and the Arabian Gulf.

ACKNOWLEDGEMENTS

Thanks always go to God, first and last, for providing me with the health and the opportunity to accomplish this study. I would like to express my thanks to the government of the State of Qatar (my home country) and the University of Qatar for their continuous financial support towards my studies in the United Kingdom.

I am extremely grateful to my supervisors Dr. Ted Milton and Professor Mike Clark for their help, encouragement and advice, which led to the accomplishment of this work.

I am grateful to the GeoData Institute, University of Southampton, for the use of their GIS computer facilities, and their advice in the production of the final sensitivity map of northern Qatar. My special thanks to James Feaver, Samuel Lo and Chris Hill.

I would like to acknowledge the help of my friend Mohammed Al- Jaidah for providing the necessary equipment for diving and acquiring underwater pictures of the oil tar in northern Qatar waters.

I would like to thank everyone who has helped me and given me advice and guidance during the course of the research, in particular: Dr. Ibrahim El-Kassas, Dr. Homaid Al-Madfa, Dr. Gabr Al-Noami, Dr A. Ali Akbar, Dr. Charles Kerr, David Emery, Abdul Rahman Al-Naama, Khalid Al-Bakri, Paul Aplin, Philip Bailey, Suha Berberoglu and Mohamed Embashi.

Finally special thanks to my parents, brothers and sisters, and to all my relatives and friends in Qatar and the United Kingdom for their encouragement, moral support and prayers. I wouldn't have made it without them.

Ali Abdulla Qassim Khamis Al-Hargan

September 1997

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CHAPTER 1

1. INTRODUCTION

1.1 THE AIM OF THE PRESENT RESEARCH

The main aim of the present research is to develop an environmental sensitivity index mapping for the coastal zone of northern Qatar using high spatial resolution airborne remotely sensed data and GIS.

1.2 ENVIRONMENTAL SENSITIVITY INDEX (ESI) MAPPING DEFINED

An Environmental Sensitivity Index (ESI) is a classification and ranking of the relative sensitivities of various geomorphic coastal environmental types on a scale of 1 to 10 in terms of indicating the persistence of oil and potential for biological habitat damage. ESI mapping is usually associated with oil spill response and contingency planning, because it provides a tool to assist spill-response coordinators and government agencies in planning strategies for protection (Gundlach and Hayes, 1978; Hayes *et al.*, 1980; Pavia *et al.*, 1982; Jensen *et al.*, 1990; Narumalani *et al.*, 1992).

ESI mapping in cartographic form, coastal types are colour coded according to rank permitting rapid identification of differences. For example, the most highly sensitive coastal types would have the highest priority for protection and are colour coded in bright red. While low sensitive coastal types would have low priority for protection and are colour coded in black. In Chapter 6, ESI mapping is discussed in more detail. In addition, classifying and ranking of the relative sensitivities of various geomorphic coastal environment types in northern Qatar and the development of the prototype ESI for the coastal zone of northern Qatar are discussed in more detail.

1.3 THE PROBLEM OF COASTAL ZONE OIL POLLUTION IN THE ARABIAN GULF

Oil pollution in the Arabian Gulf goes back to the beginning of the discovery and production of oil in the Gulf. Initially oil pollution was not a major problem and did not represent a threat to the Gulf or its ecosystem. However the world demand for oil increased, especially for oil from the Gulf. As a result, oil production in the Gulf increased dramatically and the Gulf became one of the world's busiest oil transport arteries through which more than half of the world's oil supply passes(Oostdam, 1980). With this increase the Gulf started suffering from oil pollution.

Figure 1.1 illustrates the major inter-area movements of oil at sea in 1988, and shows the importance of the Arabian Gulf as a routeway (Shears, 1990; British Petroleum, 1989). Figure 1.2, in addition, illustrates global oil pollution mapped on the basis of large numbers of records of observed surface slicks, and shows how the Arabian Gulf appears among the most polluted seas in the world (Shears, 1990; Couper, 1989; Levy *et al.*, 1981).

Various sources of oil pollution are contributing to the sea water pollution in the Gulf. These sources include: 1) refineries discharges, 2) local oil exploration and exploitation and routine handling of petroleum at ports, 3) heavy maritime transport of oil through the region, and 4) war damaged wells and tankers. More details of the major causes, the impacts, and the political response of oil pollution in the Arabian Gulf are discussed in Chapter 4.

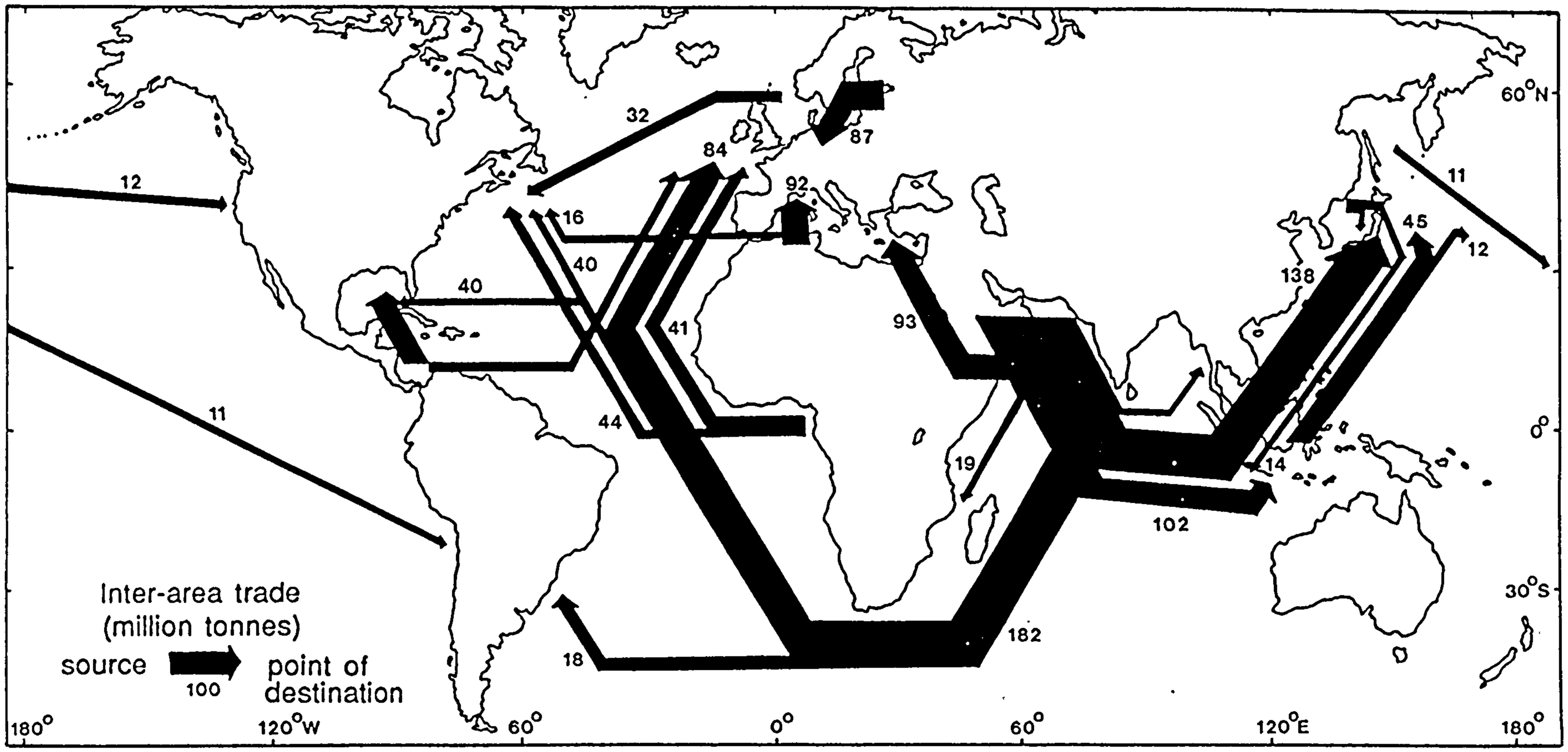


Figure 1.1 Major oil movements at sea in 1988 and how the Arabian Gulf became one of the world's busiest oil transport arteries (Source: Shears, 1990; British Petroleum, 1989).

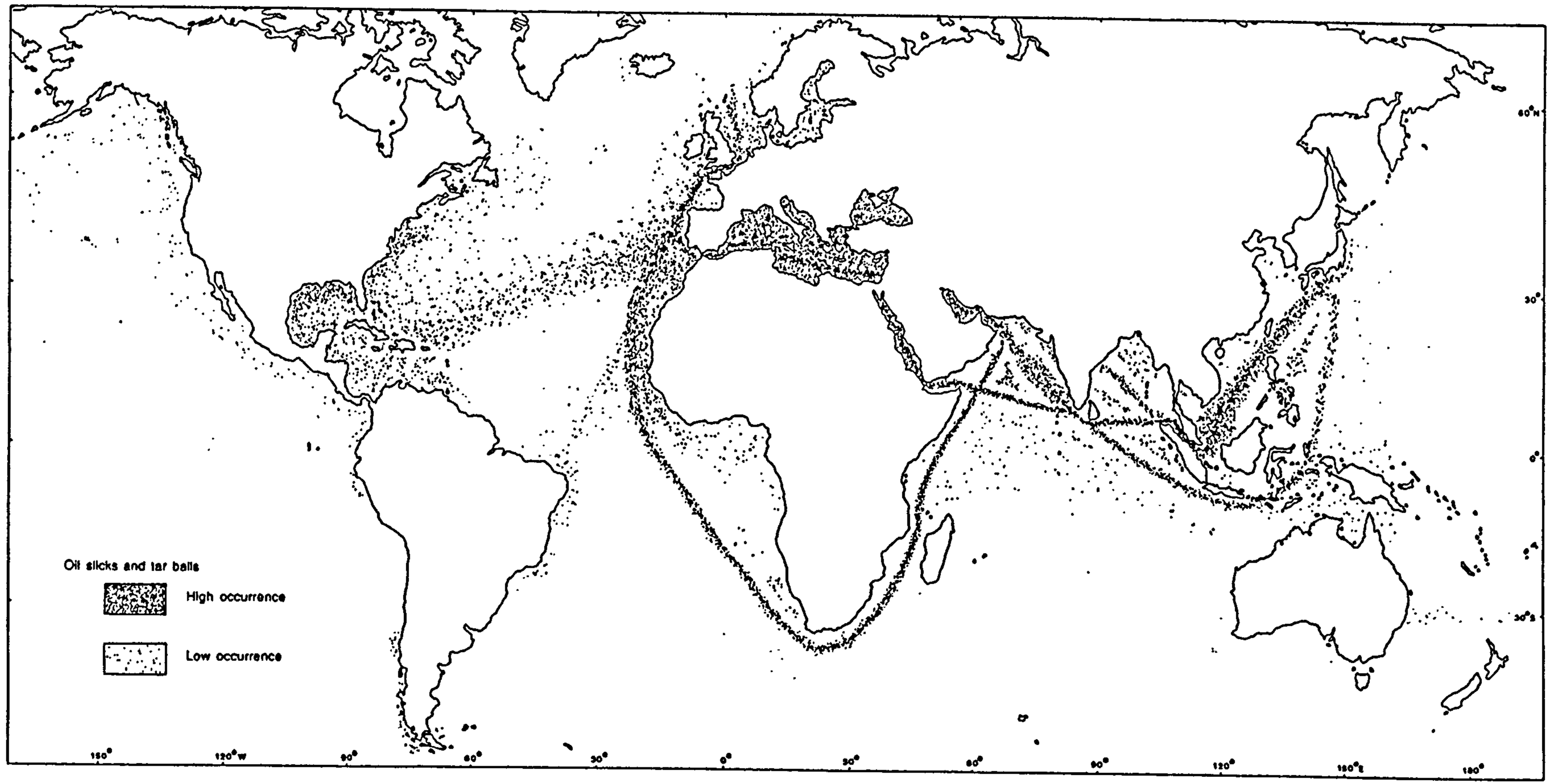


Figure 1.2 The global occurrence of oil slicks and tar balls and how the Arabian Gulf appears among those most polluted seas in the world. (Source: Shears, 1990; Couper, 1989; Levy *et al.*, 1981).

1.4 THE VULNERABILITY OF THE QATAR NORTHERN COASTAL ZONE TO MORE ENVIRONMENTAL PRESSURES

Qatar occupies a peninsula projecting due north from the Arabian shore into the Gulf. This situation makes Qatar (and especially the northern half of the peninsula) vulnerable to any oil spills that might occur in the Arabian Gulf. The northern half of the peninsula lies almost in the middle of the Gulf's water. Moreover, the surface current system in Gulf is counter-clockwise starting parallel to the Iranian side, then the Arabian side, and then flowing out through the Strait of Hormuz. Any oil spills that might occur near the shore and/or offshore in the Gulf are influenced by these hydrological conditions and moved toward the coastal zone of northern Qatar. Recent studies describing the distribution of oil pollution along the Qatari coastline show significant variations in amount. It varies from heavily polluted northern and northwestern shores to pollution-free shores in the southeast (Aboul Dahab, 1994; Aboul Dahab and Al-Madfa, 1993).

In addition to the location and vulnerability of the northern half of Qatar to any oil pollution in the Arabian Gulf, the coastal zone is composed of very sensitive and fragile coastal zone environments that can be easily damaged by oil spills. The coastline has a conspicuous uneven outline with some lagoons and sabkhahs extending inland for about 7-8 km. The characteristics of the coastal zone influence both its susceptibility to oil pollution and its suitability for survey using remote sensing methods. The environmental geology and geomorphology of northern Qatar coastal zone are discussed in more details in Chapter 3.

1.5 THE NEED FOR MARINE AND COASTAL ZONE ENVIRONMENTAL MANAGEMENT IN THE ARABIAN GULF

The coastal zone shallow water habitats of the Arabian Gulf (which include seagrass, rich intertidal zone, mangrove, salt marsh, algal mat, and sabkhah) are in fact extremely productive biologically. They support a dense population of invertebrates and form the nutritional basis on which the Arabian Gulf ecosystem depends (MEPA, 1982). Moreover, they provide the "international airports" for many migratory seabirds and marine animals. Any environmental degradation for these habitats in any country of the Arabian Gulf will result in the decline of commercial fisheries in the whole Gulf. In addition it will also further reduce the survival of many endangered animal species including those of global significance.

However, a considerable amount of environmental degradation in the Arabian Gulf besides oil pollution results from landfill, dredging and reclamation operations in the coastal zone area which started sometimes in the past and are still continuing to the present. The purpose of these operations is usually for the construction of new residential areas, causeways, ports, jetties, corniche roads and other engineering works (Sheppard *et al.*, 1992).

The Arabian Gulf has become the place for more of these operations on a very large scale. The areas chosen for these operations are often on very sensitive and biologically productive environments of the coastal zone. Human predation of marine wildlife and eggs, in addition, is a practice that taking place throughout the Arabian Gulf region which is considered an important cause limiting their population in the Gulf region. It is very important that people in the Gulf realise that these operations and activities are major causes of environmental degradation beside oil pollution and the marine resources in the Gulf (since it is an almost enclosed sea) are cross national boundaries.

Therefore, there is an important need for international environmental management and agreements between the Gulf's countries (Vousden and Price, 1985; Sheppard *et al.*, 1992) for establishing protection and conservation areas and developing environmental wildlife laws and regulations in the Gulf region which will requires a basis of formal sensitivity assessment and mapping. In Chapter 6 many of these issues are tackled in more detail.

1.6 THE NEED FOR ESI MAPPING AS PART OF THE COASTAL ZONE MANAGEMENT AND A TECHNIQUE FOR OIL SPILL RESPONSE PLANNING IN NORTHERN QATAR COASTAL ZONE

It is time now to consider the preservation of habitats in northern Qatar coastal zone more seriously. Environmental management is clearly needed for the protection of the marine and coastal renewable resources. However, managing the genuine complexities inherent in natural systems requires an interdisciplinary approach rather than sectoral. It requires understanding of the system complexity and behaviour in order to determine the future needs and responses (Clark, 1986; Sheppard *et al.*, 1992).

However, in order for coastal environmental management to proceed in northern Qatar, it requires as a first step detailed survey of the coastal zone to identify the distribution and use of coastal zone resources. Which resources are more vulnerable to environmental pressures and damage and establishment of protected areas. This is can only be accomplished by sensitivity assessment and mapping, which is being increasingly used around the world for the coastal zone management. Environmental sensitivity index (ESI) mapping provides a technique to assist response coordinators and government agencies in Qatar in planning strategies for protection.

The present research will discuss the establishment of ESI mapping for oil spill response planning in the coastal zone of northern Qatar. No such system exists for Qatar, this present attempt is the first one. Remote sensing and GIS technologies are used for enhancing the ESI mapping system in northern Qatar coastal zone. In addition, details of the development of ESI mapping for northern Qatar are discussed in Chapter 6.

1.7 APPLICATION OF REMOTE SENSING AND GIS FOR COASTAL ZONE ESI MAPPING IN QATAR

The traditional ESI mapping technique (Hayes *et al.*, 1980; Jensen *et al.*, 1990) involves the use of existing topographic charts as planimetric basemaps. Moreover, shoreline characteristics are mapped by aerial reconnaissance of the site flown at low tide and by field work. Information on the distribution of wildlife sensitivity is collected from field study and identified by symbols on the map which are designed to assess rapid response actions. Access and protection features are also depicted by symbols on the map.

However, the traditional ESI mapping concept has recently been enhanced by applying remote sensing and GIS technologies. Jensen *et al.* (1990) demonstrated the advantages of using satellite SPOT imagery to produce an up to date and accurate planimetric basemap in order to overcome the problem of lack of adequate planimetric basemap for many areas of the world. Information in shoreline ESI is interpreted from SPOT imagery using visual and digital image processing techniques. The traditional method of mapping the coastal features by viewing the terrain obliquely is very difficult especially in complex coastal zones and can introduce some errors in the final maps. Remote sensing can provide detailed, accurate and up to date information through the analysis of its digital data.

In the Arabian Gulf Landsat TM imagery has been used for the coastal zone environmental sensitivity mapping (Jensen *et al.*, 1992; Narumalani *et al.*, 1992; Narumalani *et al.*, 1993). However, the coarse spatial resolution of the satellite sensors tends to generate many mixed pixels in the image of mixed land cover materials especially in coastal zones where convoluted and complex environments are present. Coastal zones would require very high spatial resolution remote sensing sensors for detailed mapping of their convoluted and complex environments. Many of the future satellite programmes are tending toward the very high spatial resolution sensors to fill the needs of high spatial resolution satellite data.

At present high spatial resolution airborne remotely sensed data can be used to produce very detailed coastal zone ESI maps especially in areas like Qatar where full recent coverage of high spatial resolution airborne MEIS data exist for the whole coastal zone. However, handling and using such large volumes of high spatial resolution data (2m) for large coastal zone areas is a very difficult task and has not been investigated before. Chapter 5 discusses the handling and processing of airborne MEIS data for coastal zone ESI mapping in northern Qatar.

Coastal zone vulnerability to maritime oil pollution, in addition, is a complex multivariate problem characterised by both spatial and temporal trends, and as such is well suited to being handled within a GIS during the contingency planning phase (Clark, 1994). The traditional approach to evaluation of multivariate data for oil-spill contingency planning involves assembling the necessary material (maps, text, digital data and images) in hardcopy form, and manipulating them through manual techniques. Given the difficulty of applying consistent procedures within such an approach, the design of an information system to support contingency or operational response to oil spill has long been seen as an ideal (Chapter 7).

CHAPTER 2

2. POTENTIAL REMOTE SENSING INPUTS TO COASTAL ZONE GIS : A LITERATURE REVIEW

2.1 INTRODUCTION

Since the early years of GIS applications, remote sensing has always been considered as a primary source of geographic data for many geographical information systems (Townshend and Justice, 1981; Curran, 1984; Foody, 1988). With the development of geographic information systems, the emphasis has shifted from using geographic data in support of remote sensing analyses to the use of remotely sensed data as an information source for a geographic database. Generating resource information in digital form directly from digital remotely sensed data can significantly reduce the time and expense of creating and maintaining a geographic database (Aronoff *et al.*, 1987).

Remote sensing techniques have good potential for application to the complex environmental problems in coastal zones. Their potential is derived from the spatial data which can be used for the physical and ecological study of the coastal zone and marine environments. Remote sensing is generally just one tool, which should be combined with other spatial and temporal data in a geographical information system (GIS) for effective management of coastal zones (Allewijn, 1993). The combination of remotely sensed information with other (geographical) information in a GIS is essential for integrated environmental analyses. This section of the review will illustrate the applied uses of remote sensing in coastal applications and their relationship to the Qatar coastal zone. These applications are: studies of wind and currents, the detection of oil spills at sea, the detection of oil spills on coasts, sensitivity mapping, geomorphological mapping, and finally ecological habitat survey. In addition, it will also discusses the potential of fine spatial resolution satellite sensors for the next decade.

2.2 THE REMOTE SENSING OF WINDS AND CURRENTS

> "Until recently the only way to obtain sea surface velocity over large areas was to rely on measurements from ships and drift bottles. This is far from ideal, since measurements can only be made from one point at any particular time and such measurements are expensive.
>
> Using satellite data, sea surface velocities can be obtained from displacements of surface features in a time sequence of thermal infrared images."
>
> (Cracknell and Huang, 1988)

Remotely sensed imagery offers much potential in this respect and has been used for many years to interpret local and mesoscale atmospheric flow dynamics. Remote sensing of wind and ocean currents is made possible by several techniques.

Firstly, attention can be directed to those techniques which measure wind or currents directly by using the thermal and microwave portions of the electromagnetic radiation. Data from SEASAT sensors (radar altimeter, microwave radiometer, scatterometer and synthetic aperture radar (SAR)) were examined by Allan and Guymer in 1984 to measure surface wind and wave field in an area of the north east Atlantic. A comparison between sea surface observations (from research vessels and buoys) and SEASAT sensors was made with the result that the description of the wind field provided by the SEASAT sensors agreed well with the observations from the sea surface. However, it is very difficult to compare observations made at the open ocean surface with data collected by a satellite passing over with a swath width of 100 km. An easier comparison can be made with data collected from an airborne platform.

SEASAT launched in June 1978, was the first civilian satellite to carry a synthetic aperture imaging radar. Unfortunately it lived only for short time. SEASAT recorded about 126 million kilometres square of image data including multiple coverage of many regions in the world (Richards, 1993).

There are no examples in the literature of SEASAT data being used for measuring winds and currents in the Arabian Gulf region. This might be due to the short life of SEASAT satellite. Guymer and Zecchetto (1991), however, tested the SEASAT data in semi-enclosed seas and their results were promising. Most studies of the SEASAT wind measurements in the past concentrated on large-scale open-ocean situations. The SEASAT scatterometer, in addition, appears to have operated well in semi-enclosed seas.

ERS-1 (European Remote Sensing Satellite) was launched in July 1991, as the first of a new generation of satellites designed for global environmental monitoring. ERS-1 carries the Synthetic Aperture Radar (SAR), Scatterometer and the Along-Track Scanning Radiometer (ATSR), a four-band, dual-view, self-calibrating, infrared radiometer which are intended largely for sea state and oceanographic/climate research (Richards, 1993; Zavocly *et al.*, 1994; Higgins, 1995; Carver and Cotton, 1995; Howes *et al.*, 1995). It offers much potential for study of the oceans winds and currents in the Arabian Gulf and the rest of the world.

An ERS-1 SAR Fast Delivery image in near real-time was used by Silva *et al.* (1995) for guiding an oceanographic cruise in search of internal waves. SAR image over the Iberian Shelf showed the surface signatures of tidally generated internal wavepackets which gave good predictions of wavepacket position for up to four days after the satellite overpass. In April 1995 was the launch of the second European Remote Sensing satellite (ERS-2), but for some reasons instrument failure was reported later on that year.

In addition to imaging radar, thermal data from NOAA satellites have been used to detect winds and surface currents. Aguanno (1986) used NOAA-7 thermal data to detect katabatic wind activity over the Antarctic through the analysis of their temperature structure. He was able to map the general flow pattern of winds over the glaciers but not the velocity and direction, since the velocity and direction were not available from the satellite data at the time of the event.

For a more synoptic study Cracknell and Huang (1988) used NOAA-8 thermal infrared images to map the surface currents off the west coast of Ireland. Three sequential images were obtained and a thermal feature tracking technique were used. However to obtain good results, the selection of thermal features in the images must be done very carefully. General agreement was achieved between a current map derived from satellite data and current charts compiled from sea surface measurements. In addition, the satellite map showed a cyclonic eddy and sea surface front that did not appear in other field measurement charts.

NOAA images were also examined by Prata *et al.* (1990) for the Leeuwin current, Western Australia. The satellite images revealed important information about the marine habitats associated with the current. Similar investigations were made by Foerster (1993) in the Pacific Ocean. The advantage of surface ocean current maps derived from satellite data is that they are more cost-effective and up-to-date than charts compiled from field measurements.

In addition to using thermal data from satellite platforms, Davies and Mofor (1990) used thermal data from an airborne platform. Thermal band images from the Daedalus AADS 1268 Airborne Thematic Mapper (ATM) were used to study eddies generated by topographic interactions in the oceanic environment. A series of aircraft overflights of the site was carried out at different stages of a single tidal cycle. Observations are reported from a remote sensing investigation in which the process of flow separation has been demonstrated for the case of an isolated island in a tidal flow. The study has confirmed the advantage of the wake parameter in predicting the form of the eddies generated by the process of flow separation at the solid boundaries of an island in a shallow tidal flow.

Having discussed first the technique of using the thermal and microwave remote sensing for wind and ocean currents, the second possible technique is using tracers in the atmosphere such as clouds or in the water body such as sediment or foam. Turner and Warren (1989), for example, used cloud motion vectors produced using sequences of AVHRR images for mapping wind fields. They described two schemes (manual and automatic) for the generation of vectors. In such studies the registration of the images and the selection of the cloud tracers are important factors, care must be taken with both. It would be difficult to use clouds as a tracer in the Arabian Gulf and Qatar, since the region is cloud free most of the year.

A new method for feature tracking on sequential satellite images has been developed by Lewis *et al.* (1995) and Cote and Tatnall (1995) by using an artificial neural network. Clouds and sea surface thermal fronts were tracked from sequential satellite images. The method proved to be fast to execute and showed good potential for measurement of rotation and feature deformation.

In addition to measurements of wind, remotely sensed data have been used to detect ocean surface currents. For example, Pattiaratchi *et al.* (1986) examined the use of Daedalus ATM imagery for mapping tidal currents in the vicinity of an offshore sandbank. Examination of a false colour composite image revealed flow patterns which were compared with surface vector current measurement (high frequency (HF) radar and current meter data). The flow patterns showed good correlation with the field measurements of surface currents. Suspended sediment and foam were used as the passive tracer in the interpretation of the flow patterns in the image, but this technique can be affected by sun glint.

Sediment tracers could be used very effectively for monitoring ocean currents in the Arabian Gulf, since the Gulf is a shallow water body. The coastal areas of the Gulf are clear and very shallow water areas where the light easily penetrates the water column and is reflected back by the sea bottom and the sediments in the water column. Figure 2.1 represents a Thematic Mapper (TM) mosaic of Qatar, adjacent islands and shallow waters of the Arabian Gulf. This mosaic represents the blue band of TM data (0.45-0.52 μm) which has been enhanced and printed in a negative form to highlight the movement of the sediments in the water. This band has been found to be extremely useful for water-depth penetration (Lillesand and Kiefer, 1987; Narumalani *et al.*, 1993) and thus one can very easily trace the movement of sediments due to water currents. So far the only example in the literature of such application in the Gulf region is the paper published by Noweir (1990) where aerial photographs and enhanced images of Landsat Multispectral Scanner (MSS) and TM were used to monitor sedimentary processes, net sand transport and depositional features around Qatar.

Remote sensing is likely to be continued in the future as a major source of data on the ocean's topography, currents, wind stress, and surface temperature. The advantage of surface ocean maps derived from satellite digital data is that they are more cost-effective and up-to-date than charts compiled from field measurements. The ocean's winds and currents maps are very important for predicting the movement of oil spills on the ocean surface. It is very important to know and understand in what direction the spilled oil is moving to plan the protection of sensitive recourses along the coastal areas and controlling the movement itself.

So far most of the studies of using satellite or airborne images for measuring the ocean's winds and currents are not directed toward the prediction of oil spills movement. During the Gulf War and massive discharges of crude oil in the Gulf, the locations of the spilled oil on the sea surface was drown by hand on a maps through many flights over the Gulf by a helicopter. The maps are then distributed by Fax machine to the environmental protection committees of the states surrounding the Gulf to keep up dated with the movement of the spills.

Figure 2.1 TM image band 1 showing the sediment pattern in the coastal areas around Qatar.

The Gulf War oil spills are occurred between January 19th and 28th of 1991 in the northern part of the Gulf. While the mission for surveying the coastal zone of Qatar with high spatial resolution airborne multispectral MEIS digital data took place in the April-May period of 1991. The purpose of the mission is to provide Qatar with very high spatial resolution of airborne multispectral MEIS images in order to map in details the sensitive coastal resource of the country for oil spills response and planning. The MEIS images have already showed oil tar resulted from this spill covering the bottom of the shallow coastal water in northern Qatar (see Figure 5.28 in chapter 5). This is indicated that it took less than two months for the oil spill to reach northern Qatar, and if detailed mapping of the surface winds and currents of the Gulf were known at the time of the spill, better understanding and prediction of the movement of the spill could have been achieved.

2.3 THE APPLICATION OF REMOTE SENSING TO DETECTION OF OIL SPILLS AT SEA

Since about half the world's oil supply is pumped and shipped through the Arabian Gulf, oil spills and leaks have long been a problem. Between 1965 and 1976, for instance, Kuwait recorded more than 100 spills. Most of the spilled oil ends up on the coastline of the countries that border the Gulf. On January 19, 1991 during the early days of the Gulf War a large oil spill was sighted off the Kuwaiti coast. This not only affected the marine life but threatened the fresh water supply of the Gulf (desalination plants). Monitoring was initiated to provide estimates of the extent and movement of the slick. Remote sensing provided an appropriate monitoring tool and supplied the information needed by decision-makers to respond. Satellites such as meteorological satellites (NOAA) and land-oriented satellites (Landsat, SPOT and ERS-1) can be used to survey oil slicks but the repetition frequencies and the spatial and spectral resolutions of the satellite sensors limit the detection of oil. Therefore, airborne remote sensing systems are required.

Sherman (1992) provided a historical perspective of marine oil spill detection and monitoring using remote sensing. He stated that:

> " the goal of many of the remote sensing techniques was focused on Earth-orbiting satellite approaches. In reality the practical methodologies developed for oil spill detection and monitoring are most appropriate to aircraft platforms. Aircraft platforms respond well to the dynamics of most oil spills. The coupling of satellite orbits and spatial-resolution characteristics of remote sensors cannot perform the overall monitoring task. Aircraft sensors can best observe, monitor, and measure oil slicks."
>
> (Sherman, 1992).

An overview of the sensor technology options for oil spill was given by Pearlman *et al.* (1992); Fingas and Brown (1997a); Fingas and Brown (1997b); and Lunel *et al.* (1997). Table 2.1 summarises the selection of sensor characteristics for oil slick detection. Pearlman *et al.* indicated that for clear weather climates, a combination of Ultraviolet (UV) and Thermal Infrared (TIR) wavelengths will be able to map spill outline and find the location of key regions in the spill. The radiometer sensor together with the (UV/TIR) sensor could be used for measuring regions with diverse climate. A laser fluorosensor, moreover, can be used to detect the type of oil and assess oil on the shoreline. SLAR (Side Looking Airborne Radar), on the other hand, can be used to outline the spill at sea and to provide useful information for forecasting.

Sensor	Wavelength	Night Operation	Thickness Information Available	Weather Limitations	Probability of False Alarms	Image Quality
RADAR	0.3 to 30cm	Yes	No	Very Heavy Fog or Heavy Rain Moderate Wind	High	Moderate
Passive Microwave	0.3 to 30 cm	Yes	Relative Thickness	Heavy Fog or Heavy Rain	Low	Moderate
IR (Thermal Imaging)	8 to 14μm	Yes	Indicates Thick or Thin (<0.05 mm)	Light Fog	High	Good
Near and Mid IR	2.5 to 5μm	Yes	No	Very Light Fog	Modest	Good (Active)
Laser-Acoustic	1.06μm Laser	Yes	Yes	Very Light Fog	Low	N.A.
Visible	0.4-0.7μm	No	No	Clear	High	High
UV (Laser Fluorosensor)	Laser 0.308 μm Detection 0.4-0.6μm	Yes	<0.015 mm	Light Fog	Low	N.A.
UV	0.25-0.4μm	No	No	Clear	Low	High

Table 2.1 Sensor characteristics for oil slick detection (Source: Pearlman *et al.* 1992).

Fingas and Fruhwirth (1992), however, indicated that the infrared camera is the cheapest and most applicable device recommended for oil spill investigation. UV and visible devices are also recommended. A laser fluorosensor, in addition, can be used to discriminate oiled and un-oiled shoreline and to distinguish oil pollution on ice, but the device is large and expensive. Radar and SAR are also recommended, while most other sensors are experimental or do not offer good oil mapping.

Bern *et al.* (1992) discussed the Dedicated Oil Spill Experiment (DOSE-91) that took place in August 1991. The experiment was part of the project OCEANOR to develop and demonstrate a system for early oil spill detection using satellite-based Synthetic Aperture Radar (SAR). SAR images from the ERS-1 satellite were used in this project. The experiment released three oil spills (20 tons each) on the sea surface. The three slicks were mapped by surface drifter, field personnel, aircraft and the ERS-1 satellite using full image mode SAR.

During the experiment, the SAR images revealed that the SAR on board the ERS-1 satellite was able to detect oil slicks. However, the signature strength of the oil in the SAR image was a function of its type, amount, age and the environmental condition at the time of the satellite overpass.

Asanuma *et al.* (1986) used the AVHRR on NOAA-7 to detect oil spills from the Nowruz oil fields in the Arabian Gulf. The visible channels of the system revealed the possibility of detecting smoke from the oil fields in the sea. Furthermore, the radiant temperature difference between two thermal channels showed the possibility of slick detection. Zainal and Robinson (1992), in addition, used NOAA imagery for the same purpose of detecting oil spill but from Kuwait oil fields. The mid-infrared and thermal channels of the NOAA images acquired during the afternoon showed the position and extent of the slick.

Bader and Kwarteng (1992) used AVHRR and TM images of the Gulf to study the 1991 Arabian Gulf oil spill. They found that the AVHRR thermal bands were very useful and consistent in monitoring the movement of the spill and distinguishing it from the surrounding sea water. However, as the time passed, the oil was converted into mousse and smaller patches of slicks, and due to the coarse spatial resolution of the AVHRR (1.1 km), the thermal bands were unable to map these slicks. On the other hand, principal component analysis of the TM bands allowed mousse to be distinguished from the sheen.

In summary we see that the technology of remote sensing is available to detect and monitor oil spills at sea but much research needs to be undertaken to understand the limitation of each sensor available in the market today. Radar remote sensing seems to have good potential in monitoring oil spills. Most of the remote sensing data used in the Gulf for measuring oil spills has been either AVHRR or TM images. SAR on board the ERS-1 satellite will provide the opportunity of using radar images in such application in the Gulf region.

2.4 THE APPLICATION OF REMOTE SENSING TO DETECTION OF OIL ON COASTLINES

During the Gulf War, two United States Coast Guard Aireye Falcon Jets with SLAR sensors were used for the first time in the Gulf to study the oil spills that were released during the time of the war. SLAR imagery identified several new sources that were contributing oil in the coastal area of Kuwait. One source was from a channel north of Bubiyan island and two were located in the Khawr Abd Allah (Rodstein and Ott, 1992).

Narumalani *et al.* (1993) described the research that took place in two bays on the eastern coast of Saudi Arabia to assess the habitats in that region before the Gulf War oil spill. Landsat TM data and intensive field work were used in the research. Image processing and classification techniques together with verification were used successfully to establish an accurate pre-oil spill baseline habitats map.

Taylor (1992) outlined the field spectral measurements collected of Prudhoe oil on water and beach materials which took place during the Exxon Valdez spill in Prince William Sound. These measurements were made in order to provide ground spectra for verification of MEIS II imagery collected during the spill. A Spectron Engineering SE590 spectroradiometer (400 to 1000 nm) was used to characterise Prudhoe crude and different beach materials. In addition, to predict how different amounts of oil would change the spectra of beach material, a spectral mixing model was applied.

The result showed that Prudhoe oil has a very dark and uniformly flat reflectance spectrum and that a thin layer of oil will mask the spectrum of the underlying water. Beach materials in Prince William Sound also have flat spectra but are more reflective than the spectrum of oil and they do not have characteristic absorption features. Materials such as rock, weed, lichen, mussels, barnacles and drift wood are spectrally distinct and are present over large enough areas to be visible in the MEIS II data (2 m spatial resolution). Therefore, these materials can be masked when covered with oil and can easily be mapped from the backgrounds by using high resolution multispectral devices such as MEIS II.

2.5 REMOTE SENSING FOR ENVIRONMENTAL SENSITIVITY MAPPING

Jensen *et al.* (1990) described the application of remote sensing and GIS for oil spills environmental sensitivity mapping. Remote sensing and GIS can enhance the concept of environmental sensitivity mapping by using SPOT panchromatic image to produce a planimetric basemap to overcome the problem of lack adequate planimetric basemaps for many areas of the world. In addition visual and digital image processing techniques are used to extract the information needed for a shoreline environmental sensitivity index from the remotely sensed data. A GIS system is used to store information on oil-sensitive wildlife, access and protection for interfacing with a relational database for rapid access and query.

Similar studies are carried out by Narumalani *et al.* (1992) and Jensen *et al.* (1992) in Florida, United Arab Emirates, and Saudi Arabia. Landsat TM data are used for the environmental sensitivity index mapping. However, the spatial resolution provided by the Landsat Thematic Mapper sensor (30 m) is not high enough to map the small details of the coastal areas. The spatial resolution of the present satellites creates a problem by those pixels (mixed pixels) which are not completely occupied by a single category. In the mixed pixels, the pure spectral responses of specific features are mixed together with the pure responses of other features (Campbell, 1987). As a result a composite signature response is formed which does not match the pure signatures that we wish to use to classify and map the coastal zone.

During the present study, analysis of the high spatial resolution airborne MEIS data (2m) covering the extreme north of Qatar revealed important information about the behaviour of oil spills in the shallow coastal area of northern Qatar. It is found that during an oil spill, the oil is drifted from offshore area by the high currents toward the shallow coastal area. Some oil will be deposited on the shores while large amount of oil will be covering the bottom of the shallow water area (Chapter 4: Figure 4.4, Figure 4.5 and Chapter 5: Figure 5.28). This is because in the coastal areas sand tend to stick into the oil which make it heavy so that it can not float on the surface of the water. As a result the oil start to sink and cover any life in the bottom of the shallow coastal water areas.

2.6 REMOTE SENSING IN COASTAL GEOMORPHOLOGY

Remote sensing has been very useful in studying, describing, mapping and delineating coastal geomorphology. It offers especially great potential for areas that are difficult to reach by traditional ground methods. Many of the coastal geomorphologic studies we see today have used data from remote sensing. The shallow coastal waters of the Arabian Gulf and the cloud-free skies make this region ideal for examining the potential applications of remote sensing in coastal geomorphologic studies. In addition, remote sensing has been used to study landforms in the shallow coastal waters of the Gulf.

Al-Hinai *et al.* (1987) examined Landsat MSS images to study possible submerged sand dunes in the coastal area of eastern Saudi Arabia. In relatively clear water (8 to 10 m deep) a large area of sandbanks was discovered by digital enhancement of the MSS images. A masking technique was applied to the data in order to separate the land areas from the sea areas and then the contrast of each was enhanced independently. This revealed that these sandbanks may have been submerged aeolian dunes.

In a similar study El-Kassas and Noweir (1988) studied Landsat MSS data covering the shallow sea water area between Bahrain island and Qatar. Their work was aimed at studying the morphology of that area and its tectonic style in relation to the Arabian Gulf region. Black-and-white images of MSS bands 4, 5 and 7 and false-colour composites were visually interpreted for the various morphological and structural features. In addition, a colour-sliced image of MSS band 4 was used to investigate the bathymetry and underwater features. Their results indicated that the area was subject to the interference of two major folding systems called the Arabian and Zagros.

Prost (1988) also used Landsat MSS data to map the shallow sea bottom features in the clear waters between Qatar and the United Arab Emirates (UAE). Prost used a similar technique to the one used by El-Kassas and Noweir, that of density slicing MSS band 4 data. This band was designed for water-depth penetration and coastal zone mapping (Lillesand and Kiefer, 1987). Additional techniques such as band ratioing of bands 4/5 and principal components analysis of bands 4, 5 and 7 were also used in his study. As a result of the remote sensing techniques applied and the combination of the clear water environment and uniform carbonate bottom lithology, the mapping of structural features to a depth of 20 meters was achieved. Similar techniques have also been used in less favourable areas, for example Benny (1980) extracted land-water boundaries of the Bristol Channel area from a Landsat MSS band 7 (0.8-1.1 μm) image. A computerised interpretation (density contour-threading) was applied to display the land-water boundaries and sandbanks.

In addition to investigating coastal landforms, remote sensing has been applied to study the sedimentary processes of net sand transport and depositional features around Qatar. Noweir (1990) used the visual interpretation of aerial photographs and enhanced MSS and TM images in such an application. The photographs and images revealed consistent net sand transport direction during the varied periods of time and showed various coastal and offshore depositional features. A map showing the net sand transport directions of the sea floor around Qatar was produced. For future studies this sediment movement can be used as a tracer to study and understand the surface current movements in the region (Figure 2.1). Moreover, most of the coastal areas in the Arabian Gulf suffer from the lack of hydrographic data, therefore, remote sensing imagery with the clear sky and water offer a valuable source of hydrographic data in these poorly surveyed areas. The wide coverage by remote sensing allows offshore shoals, reefs and islands at great distances from the mainland to be accurately positioned.

Barzegar and Sadighian (1991) used remote sensing data (SPOT HRV) to study the effects of highway construction on sedimentation in lake Urumieh, northwest Iran. The study of the satellite data showed possible partitioning of the lake in the near future. The unsupervised classification of the data revealed that the western and eastern ends of a highway bridge were acting as dams interrupting the natural movement of sediment in the lake. Accumulation of sediment at the two ends of the highway will result in the future dividing of the lake into two smaller closed basins, thus affecting the wild life environment. Such studies could also be applied to examine the effect of the causeway construction between the eastern coast of Saudi Arabia and the island of Bahrain on sediment movements. Multitemporal satellite imagery could be acquired from the receiving station in Saudi Arabia. The images could be enhanced and classified to reveal the impact of such large water projects on the environment. In India Rao *et al.* (1985) also used remote sensing to assess shoreline changes of Kerala coast. The analysis of Landsat imagery and aerial photographs revealed the causes of coastal erosion in the region.

Finally, remote sensing has been used to discriminate coastal lithologies. Wadge and Quarmby (1986) used Landsat TM and airborne ATM data to discriminate the lithology on rocky coasts around the UK. Much information on lithology was lost in the TM data due to its spatial resolution (30 m) and mixed pixels. However, the 10 meter spatial resolution of the ATM meant that discrimination between the mainly carbonate rocks of the Carboniferous age from the surrounding clastic rocks of Old Red Sandstone was possible. ATM bands 8, 11 and 2 were most useful permutation of three single bands for analysing contrasts between different lithologies in this study.

Khamis *et al.* (1990) faced the same difficulties in using TM data for classifying the surficial carbonate deposits in the eastern coast of Qatar. No airborne data were available at the time of the study, but now a large data set of high spatial resolution airborne (MEIS) data exists for the whole coastal zone which can be used in future studies and also as surrogate ground data for classifying satellite imagery.

Peddle and Franklin (1992), in addition, describe a new way of classification methodology developed for remote sensing data and based on evidential reasoning to classify permafrost (perennially frozen ground) occurrence in south-west Yukon, Canada. The system can process multisource data sets at different levels of measurement without restrictions of underlying statistical models. It required first a set of representative training data from which evidence can be derived. SPOT HRV and a digital elevation model are the digital data used for this study plus field data collected at 422 sites. Accuracy of 85% was obtained from evidential classification of permafrost field observations and 82% from SPOT imagery and a digital elevation model. This is indicated that digital remote sensing data can be used alone to detect and monitor the permafrost.

2.7 REMOTE SENSING OF COASTAL HABITATS

Coastal habitats in Qatar are mostly salt marsh, sabkhah, mangrove, seagrass beds and coral reefs of the shallow coastal water. The salt marsh vegetation is represented by two types: *Arthrocnemum glaucum* and algal mat. Coastal salt marshes, sabkhahs and submerged aquatic resources are critical habitats and sensitive to changes. Classification, mapping and building a prototype database are important tasks for the future planning and protection of these habitats. The synoptic coverage, spectral information, and cost-effectiveness provided by the remotely sensed data make it ideally suited for studies of and mapping of habitats in the coastal areas. This review therefore covers the most relevant issues concerning Qatari coastal habitats using remote sensing.

2.7.1 Remote sensing of salt marsh

> "Saltmarshes are one of the most important biological components of the estuarine system. Marshes are an extremely productive biological resource and sustain a wide variety of flora and fauna, but they are dynamic and finely balanced and as such are susceptible to disturbance, particularly from man. In heavily industrialized estuaries pollution can be a particular problem as marshes are sensitive to a number of different waste products, such as sewage, oil and heavy metals."
>
> (Shears, 1987).

Reimold *et al.* (1973) examined the use of thermal imagery to differentiate vegetation types and to estimate the primary productivity of several of these vegetation types in tidal marsh ecosystems. Visual interpretation and colour densitometry were used to quantify the image parameters and plant characteristics. Klemas *et al.* (1975) used Landsat MSS and SKYLAB-EREP (Earth Resources Experiment Package) imagery to classify cover types in the coastal zone wetlands of Delaware. The distributions of three plant colonies were investigated in detail by using automatic and visual classification techniques. Accuracies of more than 80% (for the automatic classification) and between 75% to 99% (for the visual classification) were achieved. This confirms the potential of remote sensing for investigating coastal wetlands.

Klemas *et al.* (1980), moreover, illustrated the various data acquisition and analysis techniques in remote sensing that can be used to solve environmental and resource management problems in the coastal zone. In the United States, for example, they stated that most of wetland protection laws are based on maps of wetland vegetation produced from remotely sensed data. In Qatar, satellite data have also been used to map the distribution of the salt marsh vegetation. Distinguishing between vegetation types was difficult due to the coarse resolution of the TM data and the actual size of the area covered by the vegetation (Khamis, 1989). High spatial resolution (satellite and airborne) data can be used to overcome such a problem.

Budd and Milton (1982) explored the potential of remote sensing for salt marsh vegetation in Chichester Harbour, southern England by using a Milton multiband field radiometer. Transformations of the data collected showed possible separation between vegetation types of the salt marsh. Biomass estimation was also possible from the reflected multispectral bands using the field multiband radiometer. Their work showed that this type of remotely sensed instrument is ideally suited to salt marsh vegetation studies and hinted at the potential of the bands sensed by the Landsat Thematic Mapper for this purpose.

Gross and Klemas (1986) used Airborne Imaging Spectrometer (AIS) data to map four different types of wetland vegetation canopies in Delaware. The high spectral resolution (9.6-nm-wide bands between 0.9 and 2.4 μm) and analysis of AIS data revealed important differences in the characteristics of the spectral radiance curves of the wetland vegetation canopies. The spectral region between 1.40 and 1.90 μm was considered to be the most useful spectral region in the study. As a result, the authors stated that high spectral resolution spectrometry has important value for remote sensing investigations of wetland vegetation.

Moreover, Shears (1987) used Daedalus Airborne Thematic Mapper (ATM) imagery with field spectroscopic data and botanical information to monitor salt marsh vegetation and marsh recovery from oil refinery effluent in Fawley salt marsh, England. Analysis of the data demonstrated that a simple infrared/red (IR/R) spectral vegetation index is sensitive to the vegetation and sediment types of the salt marsh. Therefore, it was used as a surrogate measure of marsh recovery and effluent effect. ATM imagery was also examined by Reid *et al.* (1986) to detect vegetation growth and sedimentation in muddy and sandy estuarine environments of Dudden and Wash, England.

2.7.2 Remote sensing of mangrove

> "Mangrove forests are the characteristic forest ecosystem of tropical and subtropical intertidal regions. They typically occur on flat lands between high and low tide level in areas with high annual precipitation. The development of mangroves takes place only on sheltered shores. Vegetation shows distinct zonation characterised by the presence of particular species of plants. The zones have specific physico-chemical environment and related dominant genus are dependent on the extent and frequency of inundation under tidal waves, salinity and soil characteristics. The freshwater and seawater mixing is a very important factor controlling the salinity and ultimately the vegetation composition. The currents also play an important role in the distribution of seeds, seedlings and plant parts."
>
> (Roy, 1989).

The stratification of mangrove vegetation types was conducted using false colour composite photographs of MKF-6 camera and panchromatic photographs of KATE-140 camera in India by Roy (1989). The two camera systems of the Salyut-7 manned spacecraft have been used to map the mangrove vegetation on the basis of type and structure. The camera systems provide stereoscopic vision on film photographic formats from the predetermined orbits of the mission over India from approximately 300 km altitude. Table 2.2 illustrates the technical details of the MKF-6 and KATE-140 camera systems.

MKF-6 Camera Specifications		
Focal length	=	125±0.5 mm
Wavelength bands	=	460 - 500 nm
		520 - 560 nm
		580 - 620 nm
		640 - 680 nm
		700 - 740 nm
		790 - 890 nm
Optics	=	f/4/124 "pinatar" lenses (six)
Image Frame Format	=	56 X 80 mm^2
Picture area	=	165 X 220 km^2
Final resolution on the Image	=	160 line pairs/mm
Ground resolution	=	15 - 20 m from 250 km altitude
		30 - 40 m from 300 km altitude
KATE-140 (Soviet Cartographic Large Format Camera) specifications		
Focal length	=	140 mm
Film	=	Panchromatic & Infrared
Ground resolution	=	30 m from 300 km altitude

Table 2.2 Technical details of MKF-6 and KATE-140 camera systems (Source: Roy,1989).

Visual interpretation of MKF-6 false colour composite (bands 2, 4 and 6) and KATE-140 panchromatic photographs (stereopairs) was used. A Landsat MSS colour composite image was used for comparison. The visual interpretation technique was carried out using parameters like tone, texture and pattern in addition to ground information. The ground information (regarding vegetation composition, density and height) was the main reference in demarcating the different strata, which was collected in 10m X 10m quadrants in the mangrove forest areas. A total of 120 sample plots were distributed in various vegetation strata.

The result showed that tonal and textural variations itself were not sufficient to delineate the strata. Landform analysis provided main guidelines in identifying vegetation types. In addition, the study showed that while the new mangrove areas are developing in recent coastal alluvium, the old mangrove areas are endangered due to blocking of drainage by silt.

The human eye is limited in interpreting vegetation types from hardcopy format. More objective results can often be achieved by using computer-assisted classification. Automated classification classifies the vegetation types based on their spectral reflectance by using a decision rule which assigns each pixel in the test region to the class of which it has the highest probability of being a member. The ground information can then be used to assess the accuracy of the classification.

2.7.3 Remote sensing of seagrass

> "Seagrass meadows are important nursery areas for a variety of prawn and fish species which are the basis of valuable commercial and recreational fisheries. Seagrass management requires effective monitoring methods."
>
> (Hyland, 1988).

Another habitat that occupies the shallow water of the northern Qatari coastal zone is seagrass, and remote sensing has been used to identify and map such seagrass beds. Landsat TM imagery was examined by Hyland *et al.* (1988) to identify seagrass in Moreton bay, southern Queensland. The beds were highlighted by image enhancement and classification techniques. Seagrasses submerged up to 1.5 meter in clear water and on exposed tidal flats were mapped from the enhanced images. No seagrass substrates were identified in the highly turbid waters of the bay, but band ratioing of infrared and red gave an indication of vegetation cover exposed in the intertidal zone.

The work done by Monaghan and Williams (1988) using TM bands ratio (3/1, 3/2 and 2/1) was also effective in defining seagrasses and removing any irrelevant characteristics of reflectance at the lake bottom and water surface (Lake Macquarie, New South Wales). In the present study it has been possible to map seagrass beds in Qatar for the first time by using airborne MEIS (Multi-detector Electro-optical Imaging Scanner) data (Khamis *et al.*, 1995). The classification technique applied showed seagrass to a depth of approximately 0.75 meters in clear waters.

2.7.4 Remote sensing of coral reef

In the area of coastal waters between Qatar and Bahrain (northwest of Qatar) there is a large distribution of coral reefs known as Fasht (Fasht is the Arabic name for reef). Zainal *et al.* (1992) monitored the marine ecological changes of this area using Landsat TM data. Classification of the data at low tides revealed some spectral similarity between most of the major habitats, and thus they became indistinguishable. To overcome this problem the researchers subdivided the TM image around the major critical habitats and classified each sub-area independently. The result indicates improvement on the accuracy of the final classified sub-area.

Sometimes, and especially in the Arabian Gulf coastal waters, the spatial resolution of TM data is too coarse to enable such habitats to be distinguished. Higher resolution airborne data are required and can be used as surrogate ground data to classify the TM data. Luczkovich *et al.* (1992) found similar difficulties in the Dominican Republic. Because of the cell size of TM data, seagrass and coral areas, but not sandy areas were difficult to distinguish in the analysis.

Kuchler *et al.* (1986) used the Great Barrier Reef as an example to illustrate the advantage of using remote sensing technology in studying coral reefs. Reef geography, form, surface cover, vegetation, micro aspects and oceanography were examined. Information collected on these with remote sensing technology is more efficient and less expensive than ship-based measurements. De Vel and Bour (1990) used SPOT HRV data to study the structural and thematic mapping of the Tetembia Reef (New Caledonia). Various substrate themes such as soft bottom, coral debris and living coral were identified.

2.8 THE POTENTIAL OF FORTHCOMING FINE SPATIAL RESOLUTION SPACEBORNE SENSORS FOR COASTAL ZONE MAPPING IN THE GULF

In the very near future, very high spatial resolution satellite imagery as fine as 1 m in panchromatic mode and 4 m in multispectral mode will be available widely for the Earth surface (Aplin *et al.*, In press). These new fine spatial resolution images offer great potential for remote sensing research and applications especially in the complicated coastal zone environment. They will provide very useful data sources for mapping the fragile and complicated coastal zone environment plus useful information for oil spill response planning.

Figure 2.2 illustrates an example of simulated 1 m multispectral satellite image covering Fremont in California, which will be widely available in the near future. The simulated image demonstrates the high information content gained by merging high resolution panchromatic data with coarser resolution multispectral data.

The availability of such data will offset the main problem of using airborne remote sensing in the Gulf region, namely the lack of any indigenous system to acquire the data. Airborne multispectral data are currently obtained from hired foreign systems, and this is expensive and involves decisions being made by those who may not be familiar with the area or its problems.

The new generation of fine spatial resolution satellite sensors will provide the Arabian Gulf with a new source of high spatial resolution imagery for mapping the coastal zone environment and help combat the continuous threat of oil spills in the region. If such imagery is made available in near real-time this will hold valuable information for decision makers and personnel in charge of cleanup operation to rescue the fragile coastal zone environment. In the longer term there is the possibility of generating detailed continuously updated ESI maps for the whole of the coastal zone environment of the Gulf. Table 2.3 presents some technical specifications about these forthcoming high spatial resolution satellite sensors.

Figure 2.2 Example of simulated 1m panchromatic data merged with 4m multispectral data covering Fremont in California, spectral bands: Near-IR, Red, Green (as R, G, B). (Source: Space Imaging Inc., 1994)

However, imagery generated from these sensors will present novel and significant challenges to all concerned, even those used to working with remotely sensed data such as Landsat TM. They will need very large computer storage space and longer processing requirements just like the airborne MEIS data used in this thesis, and if the information potential of these new high spatial resolution satellite sensors is to be realised it is important that traditional methods of classifying and interpreting remotely sensed images are not simply transferred to the new data without question. One of the primary aims of this thesis is to address this problem of how high spatial resolution data may be most effectively used in an operational context. The present thesis provides a unique example of manipulating a very large volume of remotely sensed data for a Gulf State and will help the future processing and archiving of fine spatial resolution satellite imagery. For example, the JPEG compression techniques provides a highly effective solution for storing these fine spatial resolution images at regional scale.

LAUNCH	SENSOR *MISSION*	ORGANISATION *COUNTRY*	SPATIAL RESOLUTION (m)	SPECTRAL MODE
1974	**KFA-1000 camera** *Resours-F1*	RSA (Priroda) *Russia*	**5 to 7**	Pan.
1978	**KFA-3000 camera** *Resours-F3*	RSA (Priroda) *Russia*	**2.5**	Pan.
1983	**TK-350 camera** *Kosmos*	RSA & Lambda Technology *Russia*	**10**	Pan.
1983	**KVR-1000 camera** *Kosmos*	RSA & Lambda Technology *Russia*	**2**	Pan.
1988	**MK-4 camera** *Resours-F2*	RSA (Priroda) *Russia*	**8**	MS (4 bands)
1993	**EKOS** *EKOS*	RSA *Russia*	**5 to 7**	MS (8 bands)
1995	**Kuban camera** *Kuban*	RSA *Russia*	**3 to 4.5** **3 to 10**	Pan. MS (4 bands)
1995	**PAN** *IRS-1C*	ISRO *India*	**5.8**	Pan.
1996	**MOMS-2P** *MIR*	DARA & RSA *Germany & Russia*	**6** **18**	Pan. MS (4 bands)
1996	**AVNIR** *ADEOS*	NASDA *Japan*	**8** **16**	Pan. MS (4 bands)
1997	**HSI** *Lewis*	NASA & TRW *USA*	**5** **30**	Pan. MS (2 bands)
1997	**PAN/MS** *Clark*	NASA & CTA *USA*	**3** **15**	Pan. MS (3 bands)
1997	**PAN/MS** *Earlybird*	Earthwatch *USA*	**3** **15**	Pan. MS (3 bands)
1997	**EROS** *EROS*	IAI & CSTI *Israel*	**1**	Pan.
1997	**IKONOS 1** *IKONOS 1*	Space Imaging EOSAT *USA*	**1** **4**	Pan. MS (4 bands)
1997	**Panchromatic** *IRS-1D*	ISRO *India*	**5.8**	Pan.
1998	**OES** *ALMAZ-1B*	RSA & SAR Corp. *Russia*	**2.5** **4**	Pan. MS (3 bands)
1998	**SAR-3** *ALMAZ-1B*	RSA & SAR Corp. *Russia*	**5 by 7**	Micro. (1 band)
1998	**SAR-10** *ALMAZ-1B*	RSA & SAR Corp. *Russia*	**5 by 7**	Micro. (1 band)
1998	**Orbview-3** *Orbview-3*	Orbimage *USA*	**1 and 2** **4**	Pan. (2 bands) MS (4 bands)
1998	**PAN/MS** *Quickbird*	Earthwatch *USA*	**0.8** **3.3**	Pan. MS (4 bands)
1998	**HR PAN** *IRS-P6*	ISRO *India*	**2.5**	Pan.
1998	**GDE** *GDE*	GDE Systems *USA*	**1**	Pan.
2002	**HRG** *SPOT-5*	SPOT Image Corporation *France*	**5** **10 and 20**	Pan. MS (4 bands)
2002	**AVNIR-2** *ALOS*	NASDA *Japan*	**2.5** **10**	Pan. MS (4 bands)

(Pan. = panchromatic, Ms = multispectral and Micro. = microwave)

Table 2.3 Fine spatial resolution satellite sensors in use or under development (Source: Aplin *et al.*, In press).

2.9 SUMMARY

In summary, remotely sensed data have been a major source of information (and are likely to continue to be) for the diverse nearshore marine and coastal environments. Research applications of many of the applied fields have turned increasingly to remote sensing for a partial and/or full solution. For the reason that most of the conventional research measurements can only be made from one point at a time and such measurements are expensive, while remotely sensed imagery offer much potential in this respect. Previous studies have proved that information derived from remotely sensed data are more cost-effective and up-to-date than information compiled from field measurements.

Remotely sensed data, for example, have been used for measuring winds and currents. Radar, thermal and a false colour composite images have been used to study and map winds and surface currents of the ocean and the sea in many parts of the world. The measurement of winds and currents can be made, as discussed earlier, directly by using the thermal and microwave portions of the electromagnetic radiation, or indirectly by using tracers in the atmosphere such as clouds or in the water body such as sediments or foam.

Remote sensing technology has been used also to detect and monitor oil spills at sea but much researches need to be undertaken to understand the limitation of each sensor available in the market today. Radar remote sensing seems to have good potential in monitoring oil spills. Applications of remote sensing have been used also to detect oil on coastline areas. SLAR images were used to study oil spill in the coastal area of Kuwait during the Gulf War. SLAR images identified several new sources that were contributing oil in the Gulf. TM data, in addition, were used in the eastern coast of Saudi Arabia to assess the habitats in the region before the Gulf War and to establish an accurate pre-oil spill baseline habitats map.

During the present study, moreover, oil tar covering the bottom of the shallow coastal water in northern Qatar were detected for the first time by the analysis of the high spatial resolution airborne MEIS data. MEIS data revealed important and new information about the behaviour of the oil spills around the Qatari coastlines. Field spectral measurements, in addition, were collected for Prudhoe oil on water and beach materials during the Exxon Valdez spill in Price William Sound. The result showed that Prudhoe oil has a very dark and uniform flat reflectance spectrum and that a thin layer of oil will mask the spectrum of the underlying water. Beach materials in Prince William Sound also have flat spectral but are more reflective than the spectrum of oil and they do not have characteristics absorption features. This information was used to provide ground spectra for verification of MEIS II imagery which collected during the spill.

Remote sensing technology, moreover, has been very useful in studying coastal geomorphology. In the Arabian Gulf, remotely sensed data are used to study possible submerged sand dunes in the coastal area of Saudi Arabia, to study the morphology and tectonic style of the shallow sea water area between Bahrain and Qatar, and to map shallow sea bottom feature in the clear waters between Qatar and UAE. Outside the Arabian Gulf region, Landsat MSS imagery were used to extract land-water boundaries of the Bristol Channel area.

In addition to studying coastal landforms, remotely sensed data have been used to study the sedimentary processes of sand transport and depositional features around Qatar, in Lake Urumieh (northwestern Iran), and in India. Discrimination of coastal lithologies was also applied the technology of remote sensing. Landsat TM and airborne ATM were used to discriminate the lithology on rocky coasts around the UK and the eastern coast of Qatar. Remotely sensed data and a new way of classification (evidential reasoning) were used to classify the occurrence of perennially frozen ground in Canada.

The synoptic coverage, spectral information, and cost-effectiveness provided by the remotely sensed data make it ideally suited for studies and mapping of habitats in the coastal areas. Remotely sensed data have been used world wide for studying and mapping the sensitive marine and coastal habitats such as: salt marsh, mangrove, seagrass and coral reef. In addition, they make very important source of data for the development of the coastal zone GIS:

> "with the proliferation of geographic information system (GIS) in both industry and government for numerous applications, there has been a tremendous increase in demand for remote sensing as a data input source to spatial database development. Products derived from remote sensing are particularly attractive for GIS database development because they can provide cost-effective, large area coverage in a digital format that can be input directly into a GIS."
>
> (Lunetta *et al.*, 1991)

Although data derived from remote sensing are increasingly being utilised as a data source in GIS, non of the previously discussed studies for the coastal zone were using remote sensing as a data source for the GIS except those studies by Jensen *et al.* (1990); Narumalani *et al.* (1992); and Jensen *et al.* (1992). When they discussed the utilisation of satellite data as a source of data for the environmental sensitivity mapping of the coastal areas and as input in a GIS system for interfacing it with a relational database for rapid retrieval and querying. Which therefore allow the management decisions on oil spills to be made in real time.

However, the coarse spatial resolution of the satellite sensors tend to generate many mixed pixels in the image of ground materials. In contrast, decreasing the size of the ground instantaneous field of View (GIFOV) of the sensor for a heterogeneous scene increases the variance in the data and makes purer pixels more likely (Boardman, 1994).

Many of the future satellite programmes are going toward the higher spatial resolution sensors to fill the needs of high spatial resolution satellite data. In the very near future, very high spatial resolution satellite imagery as fine as 1 m will be available widely for the earth surface. Today high spatial resolution airborne sensors can be used in such mapping. However, when the data coverage cover large areas of the earth surface, large volumes of digital data are generated which make the automated analysis and handling of the data very difficult. Such issue has not been tackled before especially in the ESI mapping of the coastal zone.

The present research deals with new study of using very high spatial resolution airborne data covering large areas for ESI mapping of the fragile coastal zone habitats for oil spills response and planning. At present Qatar has full recent coverage of very high spatial resolution airborne MEIS (Multi-detector Electro-optical Imaging Scanner) data (2m) for the whole coastal zone of the country. Which are acquired to provide detail means of information for the ESI mapping in Qatar and the planning of oil spill counter measures.

However, the nature of this airborne data set represents a unique problem of being very large volumes of digital data, because it was scanned in very high spatial resolution sensor and covered large areas of the earth surface. Handling and using such large volumes of digital data for ESI mapping are very difficult task that have not been investigated before. A problem that could also faces the future programme of the satellite higher spatial resolution sensors.

In addition, the compilation and analysis of the data acquired for the coastal zone habitats are incorporated into a coastal zone geographic information system to support contingency or operational response to oil spill. Since the traditional approach to evaluation of multivariate data for oil-spill contingency planning involved assembling the necessary material (maps, text, digital data and images) in hardcopy form, and manipulating it through manual techniques given the difficulty of applying consistent procedures within such an approach.

CHAPTER 3

3. THE COASTAL ZONE OF QATAR

3.1. INTRODUCTION

Qatar occupies a peninsula projecting 180 km due north from the Arabian shore into the Gulf. It lies between 24° 30 and 26° 10 N latitude, and 50° 45 and 51° 40 E longitude. This situation makes Qatar vulnerable to any oil spills that might occur in the Arabian Gulf (Figure 3.1).

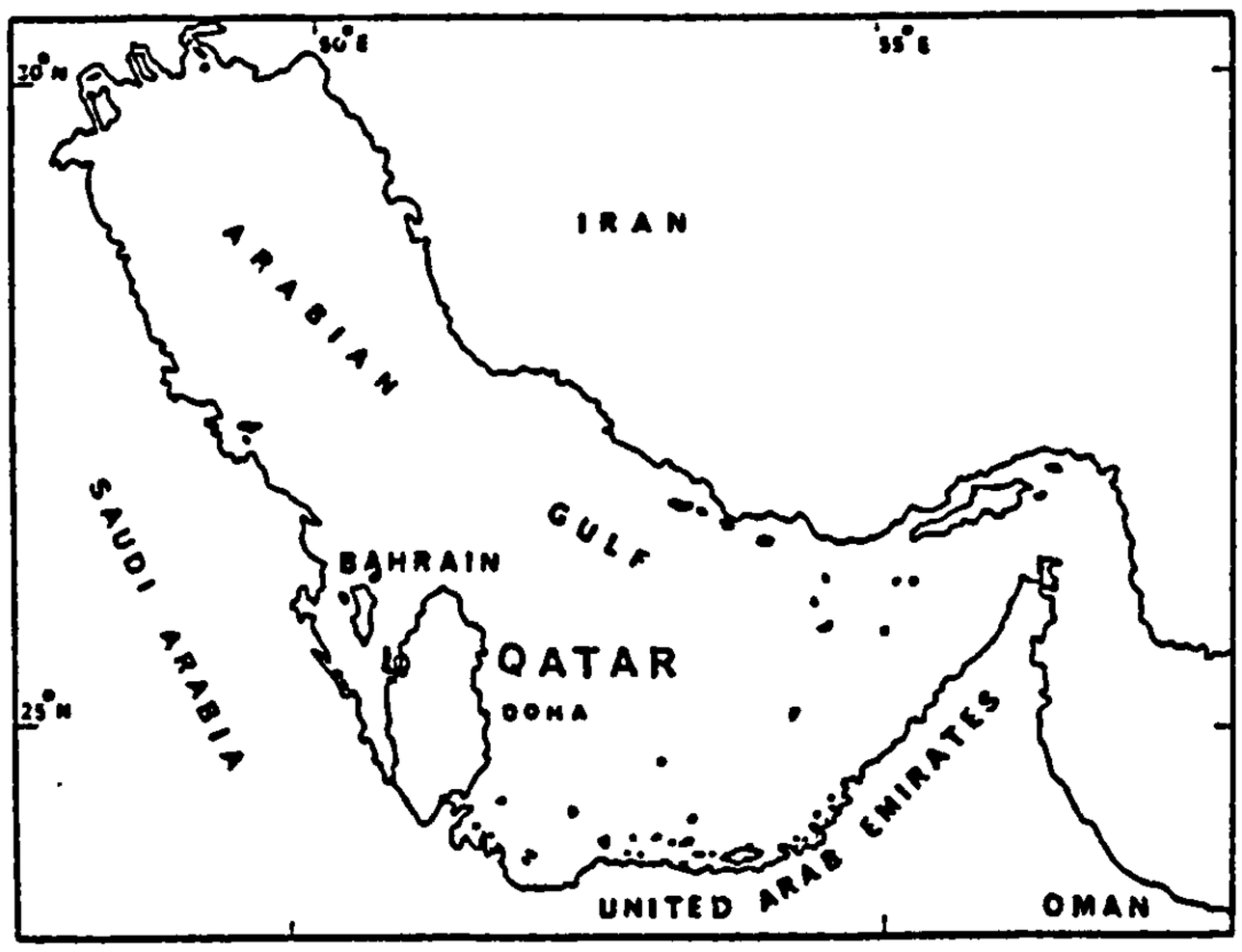


Figure 3.1 Location map of Qatar peninsula.

Aboul Dahab (1994) and Aboul Dahab and Al-Madfa (1992) describe the distribution of oil pollution along the Qatari coastline, which is characterised by significant variations in amount. It varies from heavily polluted northern and northwestern shores to pollution-free shores in the southeast. This can be attributed firstly to the location of Qatar and secondly to the meteorological and hydrological conditions in the Arabian Gulf region. The characteristics of the coastal zone influence both its susceptibility to oil pollution and its suitability for survey using remote sensing methods.

3.2. CLIMATIC AND OCEANOGRAPHIC CONDITIONS

The Qatar peninsula, being located in the arid belt, exhibits hot desert climatic conditions. Generally, the climate is extremely hot and humid in the summer from June to September, and moderate to warm in the winter. In the summer, the average daily temperature reaches 41°C and humidity remains high most of the year.

During the winter months, the wind direction is variable with the predominant direction in December being northeasterly and in February southeasterly. However, for the remainder of the year, the predominant direction is north-northwest. During the winter months, wind speeds are generally low, averaging 10-20 km/hour in the daytime but from March to the end of July the winds are steady north-northwest winds of daytime average speeds of 25-30 km/hour. This causes relatively long term strong unidirectional currents on both the eastern and western coasts of Qatar (Noweir, 1990). What happen is when the current approaches the northern coast of Qatar peninsula it branches in two, with one current moving in a line parallel to the east coast and the other moving along the west coast. When these currents flow alongside coastal embayments some of their water moves into these embayments depositing a proportion of the load of suspended sediment (Alsheeb, 1988). This situation is greatly affected by the tidal currents in the area, which, in narrow embayments, attains a speed of more than 3 knots (Al-Khayat, 1996). The tidal regime of Qatar peninsula is semi-diurnal in the west coast and diurnal on the east coast. The daily tidal range is an average of 1.0 m on the eastern coast and up to 1.5 m on the west coast (Al-Khayat, 1996).

The Qatari waters are defined as that body of water which is within the boundaries determined by the State of Qatar for the exclusive use of natural resources including oil and gas (Figure 3.2 and 3.3). This total area of water is approximately 35,000 square km, which is 15% of the total area of the Arabian Gulf (Sivasubramaniam and Ibrahim, 1982). The depth contours and general distribution of the major types of bottom sediments in the Qatari waters are illustrated in Figures 3.2 and 3.3. Within this area, the surface water temperature may vary from a low mean of 16°C in January and February to a high mean of about 34°C in August. In the deeper region, close to the Qatari boundary to the north-northeast, the low water temperatures vary between 18°C and 22°C. In the lagoons, the temperature can vary between 15°C in the winter and 40°C in the summer. The salinity of the water generally varies between 39% and 41% at the surface and tends to be 1-2% higher at the bottom (Sivasubramaniam and Ibrahim, 1982).

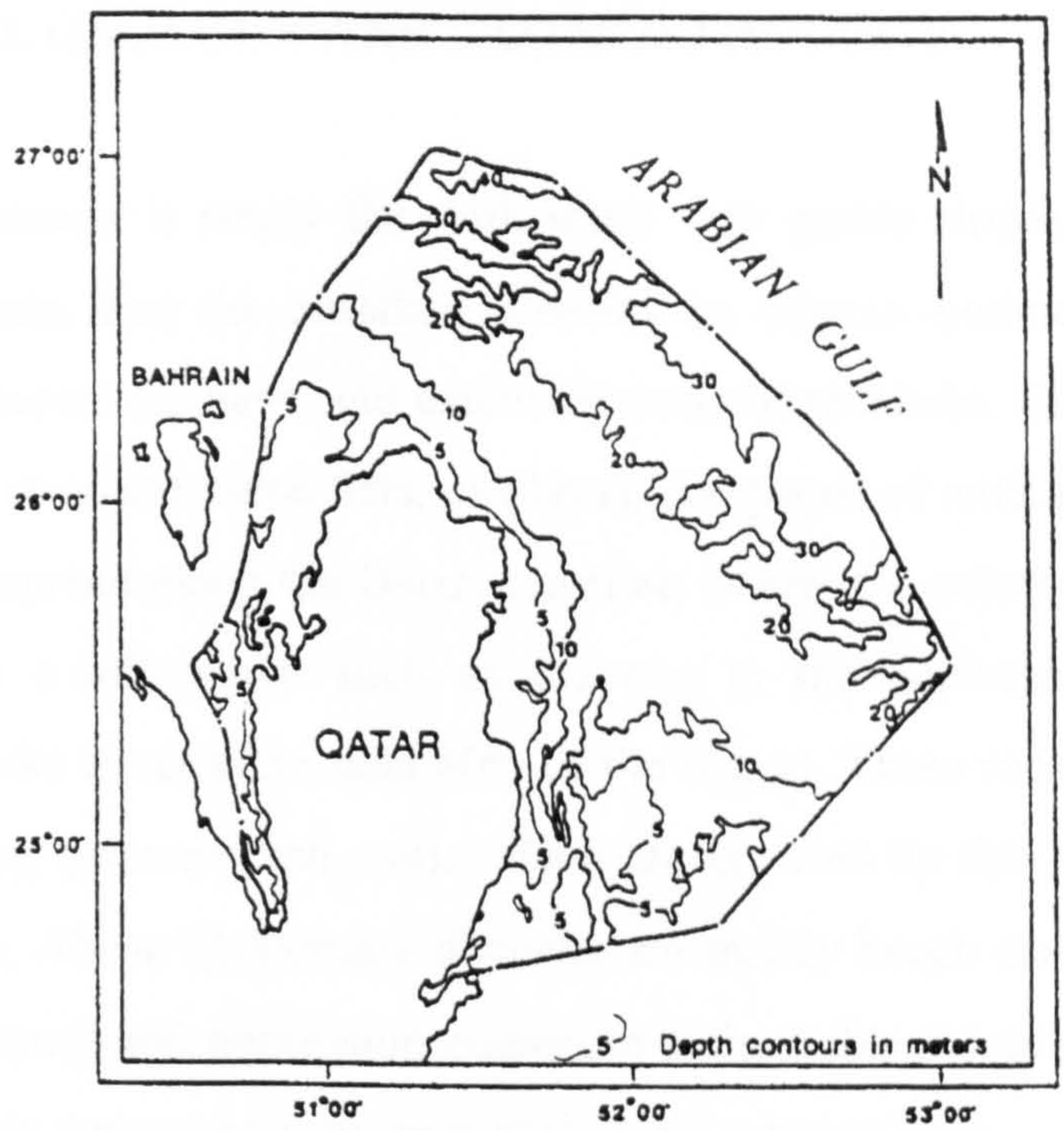


Figure 3.2 Depth contours map for Qatar waters (Source: Purser, 1973; Sivasubramaniam and Ibrahim, 1982).

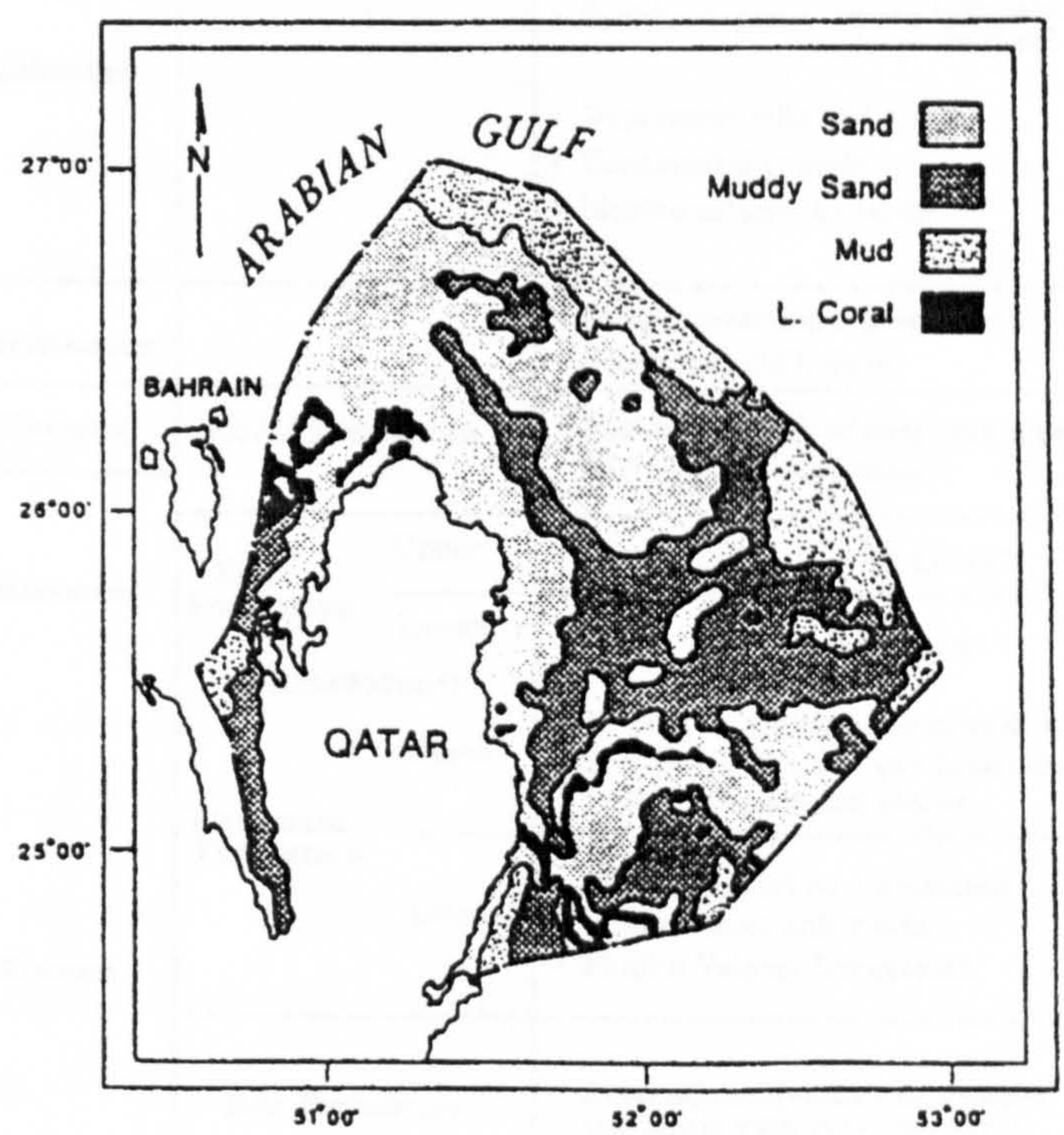


Figure 3.3 Bathymetry and sea-bottom sediment map for Qatar waters(Source: Wagner, 1973; Sivasubramaniam and Ibrahim, 1982).

3.3. COASTAL GEOLOGY AND GEOMORPHOLOGY

The Qatar peninsula is nearly flat with some very gentle slopes. The surface is low to moderate altitude, and the coastline presents an uneven outline with numerous inlets, islands, reefs, capes and bays, and extensive areas of sabkhahs. Sabkhah is an Arabic term for the coastal or inland saline flats, or playas, composed of mud and fine calcareous sand, which are widespread along the Qatari coastline. When it is colonised by halophytic plants, sabkhah forms a salt marsh such as the one in the northeastern of Qatar. Tertiary sedimentary rocks cover more than 80% of the region. These rocks are mainly limestones, dolomites, clays, gypsums and marls which are covered by thin younger deposits of the Quaternary age. These Quaternary deposits are mainly beach sands and rocks, sabkhahs, gravels, sand dunes and depression colluvium soils. Table 3.1 presents a summary of the lithostratigraphic sequence of the main rock exposures in Qatar.

Age		Formation		Lithology
Quartenary	Holocene			• Eolian sands • Sabkha deposits — Supratidal, Intertidal, Subtidal • Depression silts and muds • Continental gravels • Marine calcareous sands
	Pleistocene			• Conglomeratic and pseudoolitic limestones (Miliolites)
Tertiary	Pliocene	Hofuf Formation		• Residual gravels of conglomerates and siliceous sandstones
	Miocene	Dam Formation	Upper	• Clayey limestone with gypsum
			Lower	• Marls, clays and limestones
		Unconformity		
		Dammam Formation	Upper	• Abarug Dolomitic Limestone & marl • Simsima Dolomites and Limestones with thin marls and shales
	Eocene		Lower	• Dukhan Alveolina Limestones • Midra Shales and marls • Fhaihil Velates Limestones
		Rus Formation		• Dolomitic and chalky limestones and marls with gypsum beds in the lower parts

Table 3.1. Lithostratigraphic sequence in Qatar (Noweir and El-Kassas, 1988 a).

3.3.1. The Study Area

The study area comprises only the coastal zone of the northern half of Qatar (Figure 3.4), for the reason that this area is the most vulnerable to any oil pollution in the Arabian Gulf. In addition, the coastal zone of the northern half of Qatar is composed of very sensitive and fragile coastal environments that can be easily damaged by oil spills. The coastline of the study area has a conspicuous uneven outline with some lagoons and sabkhahs extending inland for about 7-8 km.

The study area, as part of Qatar peninsula, has been the subject of some regional geological, geomorphological and ecological studies, including mainly the works of Cavelier (1970), FAO (1973), Seltrust Engineering Ltd. (1980), Batanouny (1981), Eccleston and Harhash (1982) and Alsheeb (1988). Furthermore, other studies have been concentrated on the northern part of Qatar for particular investigations, such as a survey of freshwater resources in northern Qatar (Le Grand Adsco, 1959), the carbonate coastal accretion in northeast Qatar (Shinn, 1973a), the Recent intertidal and nearshore carbonate sedimentation around rock highs to the east of Qatar (Shinn, 1973b), drainage mapping and hydrogeological investigation of three major depressions in northern Qatar (El-Kassas *et al.*, 1985), and a study on V-shaped parabolic dunes and longitudinal sand ridges in northeast Qatar (Noweir and El-Kassas, 1988b).

3.3.2. The Environmental Geological and Geomorphological Investigation of the Study Area

The coastal zone of northeast Qatar peninsula (from the south of Al-Khawr to the north of Al-Dhakhirah) is considered to be environmentally the most sensitive area along the Qatari coast. The land of the area is characterised by a nearly flat surface of low to moderate altitude, with very gentle slopes eastwards to the Arabian Gulf. It is characterised by different types of lithologies of marine and continental origin, ranging in age from early Eocene to Recent. The area shows various geomorphologic features formed by different erosional and depositional processes, as well as by the effect of neotectonics (Khamis *et al.*, 1990).

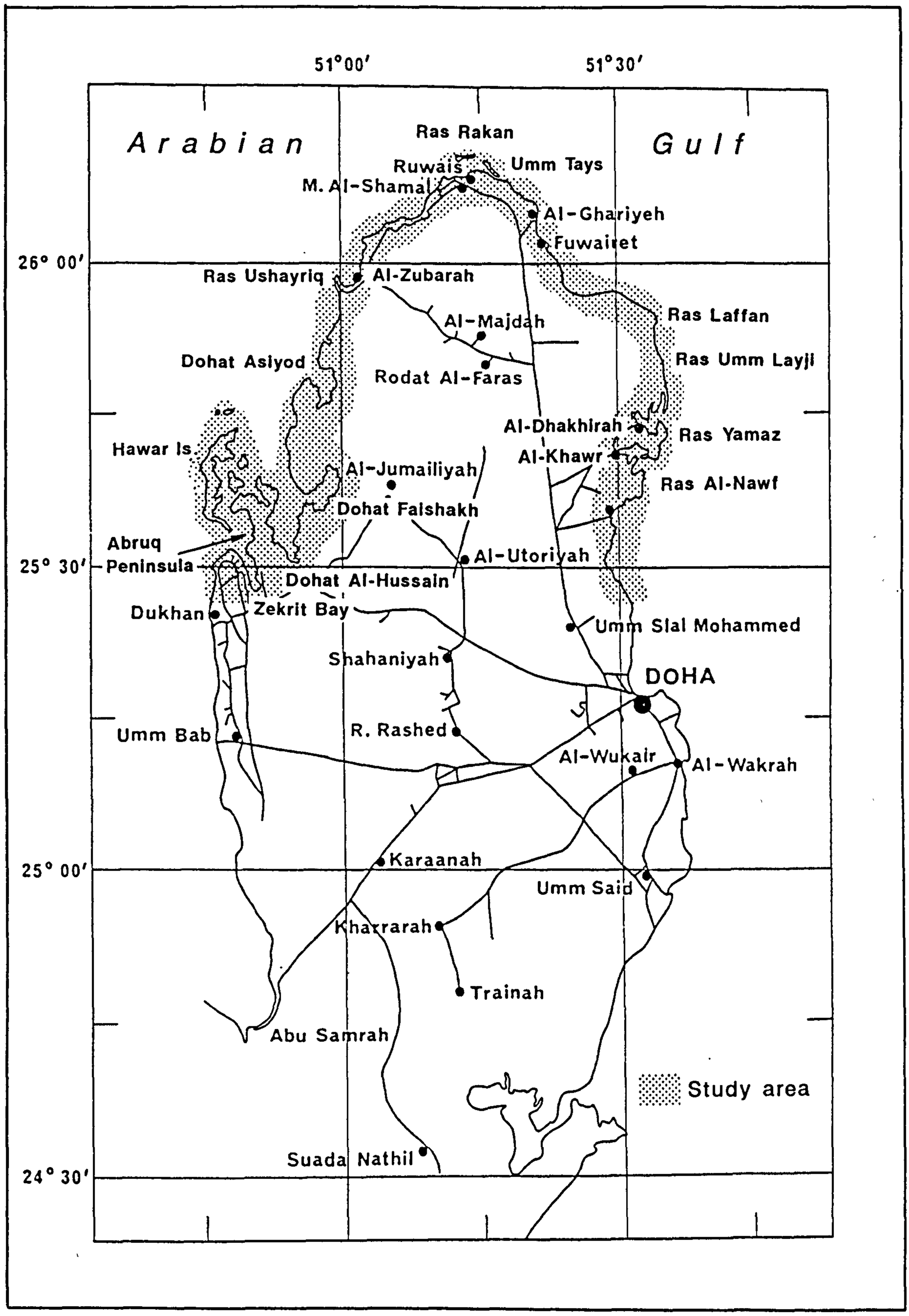


Figure 3.4 Map of the study area.

The majority of the area is covered with dolomitic and limestone rocks of the Upper Dammam Formation of Middle Eocene age. However, older rocks of the Rus Formation of Lower to Middle Eocene age are exposed in some localities particularly around the Al-Khawr and Al-Dhakhirah embayments. These exposures have been mainly formed by the effect of local anticlinal and domal structures. At the present, these exposures represent dead cliffs, which are no longer directly affected by wave erosion because of the accumulation of beach material and changes in sea level such that wave action has been excluded from the cliff foot.

Longshore currents have transported coarse-grained carbonate material from the north of the Qatar peninsula and have created chenier beaches with hook-shaped spits at their ends, where they protect some embayments behind. On the other hand, fine-grained carbonates and muddy sediments have accumulated in some of these embayments to form wide supratidal flats (sabkhahs). Sedimentation has continued between consecutive cheniers where a complicated tidal channel system was developed on the sabkhahs behind and between these cheniers and spits (Figure 3.5). Specific communities of halophytic plants (mangroves, *Arthrocnemum glaucum* and algal flat) colonise the muddy sediments of the tidal flats and channels, at various densities (Figure 3.6). However, some landward spits have become cemented around their intertidal borders forming beach rock (Shinn, 1973 b; Focke *et al.*, 1986).

This coastal muddy sediments environment of northeast Qatar is important for many marine living animals. A large number of crabs, gastropods and other organisms feed on the organic material in the muddy sediments. In addition, and because of the halophytic plant communities, the area is a notable breeding and resting area for a large number of sea birds.

Figure 3.5 Low oblique aerial photograph of the tidal channels in the sabkhah area of northeastern Qatar (Focke *et al.*, 1986).

Shinn (1973b) characterised the sabkhah deposits in the northeastern Qatar into three categories: 1. subtidal sediment, 2. intertidal sediment and 3. supratidal sediment. The subtidal sediment occurs in the lagoons or open sea, which are always below the low tide. These sediments consist of mixtures of pelleted mud and silt-sized carbonate, which are predominantly gray in colour and contain different amounts of winnowed skeletal grains. These sediments also contain about 30% dolomite, which originated from aeolian dust deposited during high wind and/or was washed from the Tertiary rocks during sporadic rains.

In addition, these sediments also have a salt-and-pepper appearance, a result of the sand accumulations that contain gray carbonate mud and silt which occur as winnowed lags in channels and as a thin narrow belt moving seaward to the east. These subtidal sediments underlay all intertidal and supratidal sediments that cover the floors of all lagoons in Qatar, and have a thickness of more than 8 meters.

Intertidal sediments are made up of the same sediments as those in the subtidal zone, but can be distinguished by their light tan colour and the presence of many iron-stained root tubes and small holes. The width of this zone of intertidal sediments can vary between a few meters to a kilometre. When the zone is wide, the sediments tend to be more muddy and many small, meandering tidal channels occur. On the other hand when it is narrow, the sediments tend to be more sandy with no occurrence of tidal channels. In the wide, muddy areas of the intertidal zone grow numerous different colonies of mangroves, salt grasses and algal stromatolites (algal flat).

Supratidal flats are interfaced landward by Tertiary outcrops and seaward by intertidal flats and chenier beaches. The sediment thickness of supratidal flats may exceed 50 cm and in many parts of the sabkhah surface evaporite crusts of 2-3 cm occur. More fixed pellet-rich muds and lags of skeletal sand 2-3 cm thick are found in supratidal sediments than those of intertidal sediments.

Figure 3.6 Communities of halophytic plants in the sabkhah area of northeastern Qatar.

Figure 3.7 Seagrass beds in the shallow water of northern Qatar coastal zone.

From northern Al-Dakhirah sabkhah to Ras Laffan in the northeast and Umm Tays in the extreme north, the coastal zone is characterised by low relief with the occurrence of some inland and coastal sabkhahs and widespread windblown sands. The occurrence of the eolian sands has its widest extent where the coast faces the prevailing northwesterly Al-Shamal winds. The winds do not form dunes, but rather thin widespread accumulations of calcareous sands of marine origin. The coastline is characterised by sandy beaches made up of the same calcareous sands with sea shell fragments. The beaches are characterised by a well-defined sloping face. Only in Fuwayrit does the coastline form an active cliffed coast.

The second environmentally sensitive coastal zone along the Qatari coast, after the sabkhah in the northeast, is the north tip of Qatar (from Umm Tays to Ras Rakan). The land of this area is characterised by a flat surface of low relief, with very gentle slopes northwards to the Arabian Gulf. It is characterised by different types of lithologies of marine and continental origin, ranging in age from early Eocene to Recent. Small areas of inland and near coast sabkhahs are scattered in the north and northwestern of the peninsula. A wide intertidal zone of shallow water is interfaced landward by the mainland and seaward by two offshore bars (Ras Rakan and Umm Tays islands).

Ras Rakan and Umm Tays islands run almost parallel to the coast of the northern tip of Qatar peninsula, making the intertidal area semi-sheltered. Compacted sediments of mud and silt-sized carbonate form the floor of this semi-sheltered intertidal zone. In addition, very small offshore sandy bars are scattered in the vicinity of the shallow water between the two islands. Beds of seagrass inhabit the muddy sediments of the shallow water making this area very high in biological value (Figure 3.7). The seagrass beds are also a feeding area for the most popular and expensive fish (*Siganus canaliculatus*) in Qatar and the Gulf region (Khamis *et al.*, 1995).

Artificial riprap of boulder-size quarried bedrock has been placed systematically in the intertidal zone to catch fish. During the high tide, the water covers the whole intertidal zone and the riprap. The fish come with the tide to feed in the seagrass beds of the area. During the low tide the fish trapped in the riprap with the remaining shallow water ready for the people living in the small villages in northern Qatar to come and collect the fish.

Moreover, along the southern sides of both islands (Ras Rakan and Umm Tays) which are facing the intertidal zone, are communities of saline flat plants (*Arthrocnemum glaucum*). The height of these plants varies between 25 cm and 75 cm in some areas (Figure 3.8). Since this area is far from outsider disturbance, it has become an ideal salt marsh for a large number of water birds. Water birds such as *Socotra cormorant* and *Kentish plover* use this salt marsh as a breeding and resting area (Khamis *et al.*, 1995).

From the north and west of Ras Rakan island to almost to Ras Ushayriq in the north northwest, the coastal zone (especially the intertidal area) is exposed to the full force of the dominant northwestern winds (locally known as the Al-Shamal wind). This coastal zone is known to be the main source of carbonate sediments along the Qatari coast (Focke *et al.*, 1986; Noweir, 1990). Much of the sands we see today on the beaches of Fuwairat, Gharya, Ras Laffan (in the north northeast of the peninsula) and the chenier beaches in the northeast were originally formed in this coastal zone (Focke *et al.*, 1986; Noweir, 1990).

The sands of the northern Qatar are formed from the skeletal debris of sea shells, corals and algae. Patches of rocky corals are scattered in the shallow water of the area (Figure 3.9) between low water mark and about 6 to 8 meters in depth. They extend from Ras Rakan to Abruq peninsula with a total distance of about 50 km. The geology of the land is very similar to the previous areas. It is characterised by low relief Tertiary outcrops and Recent surficial deposits. Small scattered areas of sabkhah and beach rock are also found along the coast of the area.

Figure 3.8 *Arthrocnemum glaucum* plants along Ras Rakan island in northern Qatar coastal zone.

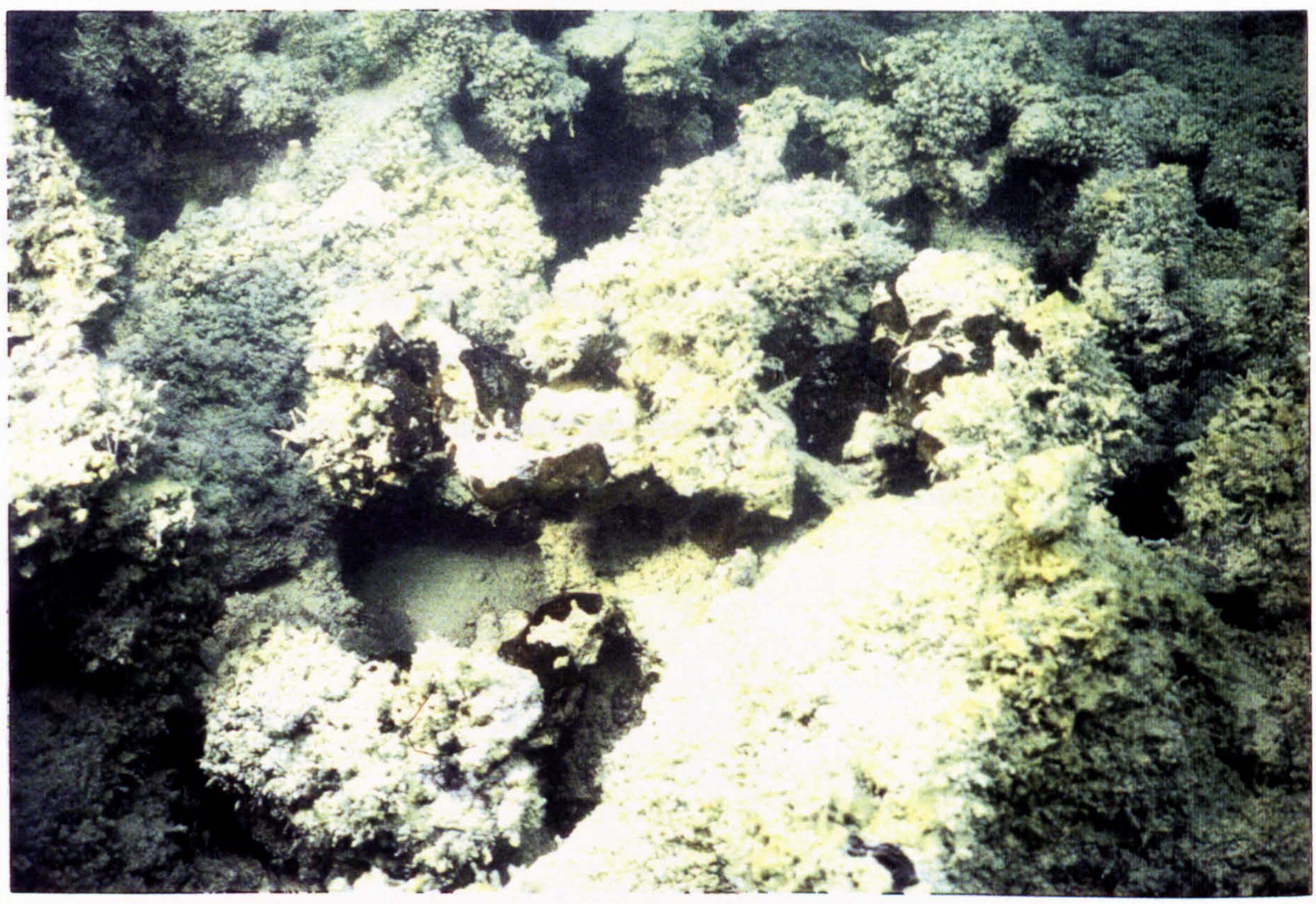
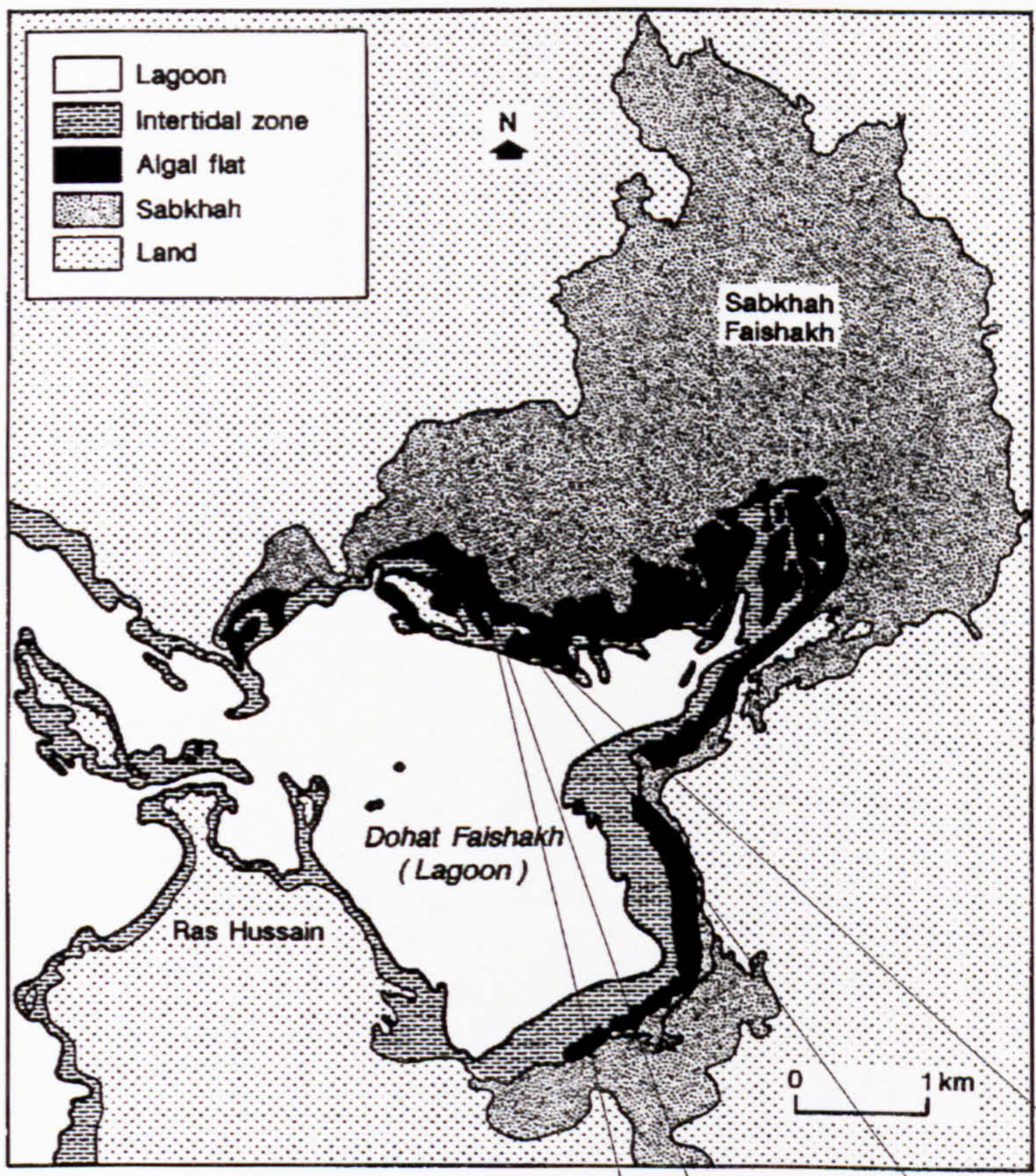


Figure 3.9 Rocky coral covered by oil tar in the shallow water of northern Qatar coastal zone.

The west and northwestern coast of the Qatar peninsula is characterised by several embayments, locally called Dohat, such as Dohat Bin Rahal, Dohat Umm Alma, Dohat Asiyod, Dohat Faishakh, Dohat Al-Hussain, and Zekrit Bay (Figure 3.4). Most important is Dohat Faishakh because it provides a unique example in coastal geology of Recent marine sabkhah development under stable sea-level conditions. It is a sheltered embayment of a semi-circular lagoon, extending for 4 km in both north-south and east-west directions. The open water lagoon has an average water depth ranging between 2 and 3 meters, with a maximum depth of 3.7 meter. The lagoon floor is covered by muddy sediments of peolidal micrite containing small lamellibranchs, gastropods and foraminifera.

The northern shore of the lagoon is flanked by a flat, intertidal area about 300 meters wide that is covered by dark-coloured, rubbery sheets of bluish-green algae that trap sediments carried in the tidal waters (Figure 3.10). The resulting sediments are well laminated, and are characteristic of the algal flat environment when they are subsequently buried by supratidal sediments and dolomitized (Blatt, 1982; Focke *et al.*, 1986).

Inland from the algal flats and above the level of the normal high tides lies a surface of supratidal mud flats (sabkhahs). These sabkhahs surround Dohat Faishakh lagoon, particularly from the north where they extend for some 5 to 6 km in an east-west direction. However, the sabkhah zone runs almost parallel to the west coast of Qatar peninsula, and in some places it may cover wide areas. When strong onshore winds combine with high spring tides, broad areas of this sabkhah are flooded. Subsequent intense evaporation causes upward movement of concentrated brine, with the resultant precipitation of an evaporite crust.



(Source: Blatt, 1982).

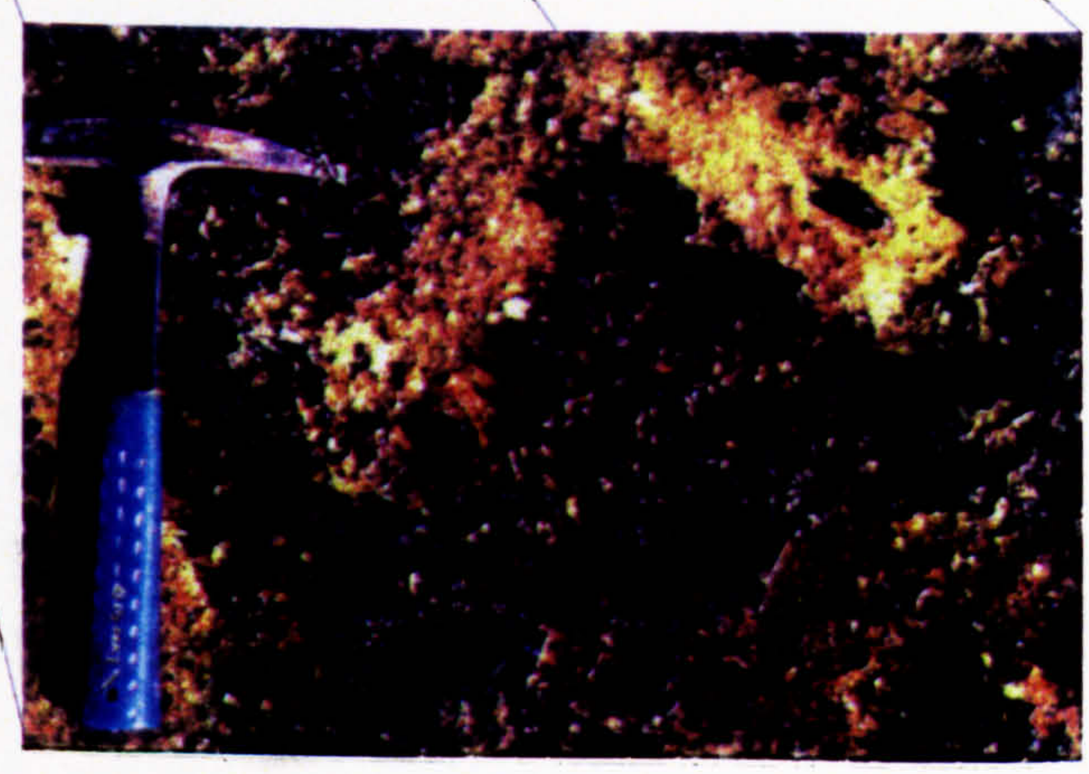


Figure 3.10 Map of Dohat Faishakh (northwest Qatar) showing the distribution of sabkhah and algal flat.

Along the eastern and western margin of this sabkhah flat, there are some elevated shoreline features that limit its further expansion. Subsequent to the water loss from the sabkhah by evaporation, seawater moves in from below the water table to the evaporative surface. With this cycle, the sabkhah area is increasing in size at the expense of the lagoon which is subjected to significant shoaling due to the constant deposition on its floor. It is expected that the lagoon of Dohat Faishakh will eventually be transformed into a sabkhah that will cover the present lagoonal area.

To the west of Qatar and not far from the mainland, the Hawar islands are located in a shallow water environment. These islands consist of a large elongated island lying parallel to the coastline and surrounded by small semi-circular islands. Parts of these small islands are submerged during the high tides. The Hawar islands are characterised by a wide intertidal zone of sand banks and sandy beaches. The islands have been used by a large number of water birds for breeding area.

In summary, it has been recognised through the discussion of this chapter that the northern coastal zone of Qatar comprises different geologic and geomorphologic environments. In addition various communities of halophytic plants colonised the muddy sediments of the intertidal sabkhah making this area ideal salt marsh for many living animal. Seagrass bed also inhabited the muddy sediments of the shallow water which are of high biological value. All of which are sensitive to oil pollution for a certain degree.

Figure 3.11 and table 3.2 represent a synthesis of all those different environments that exist in the coastal zone of northern Qatar. Landsat Thematic Mapper (TM) band 1 mosaic was visually interpreted for the mapping of those coastal environments. The next chapter of this thesis will discusses how previous oil spills and oil-related development along the coast of the Arabian Gulf affected those coastal environments. Examples from the eastern coast of Saudi Arabia and northern Qatar will be illustrated.

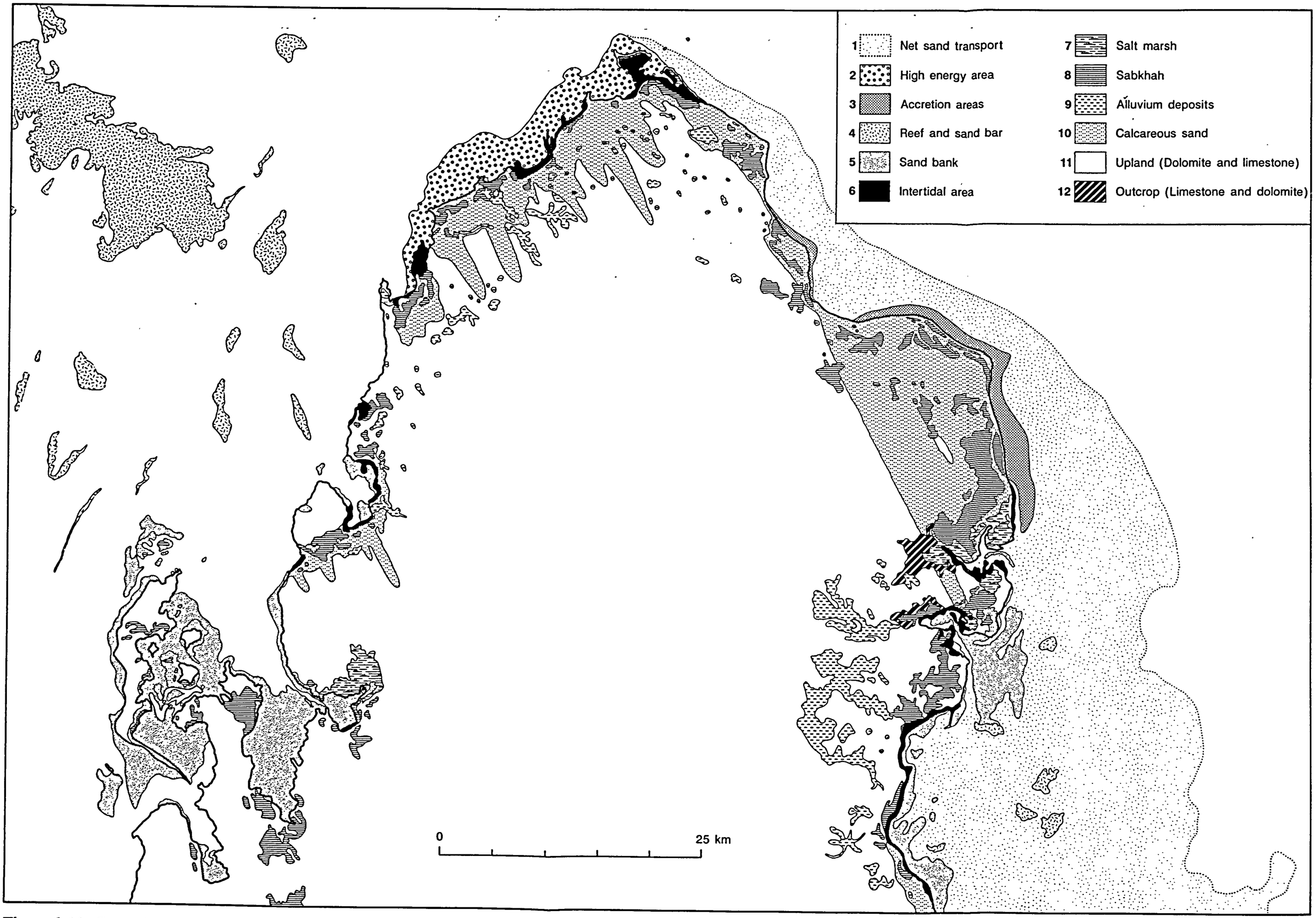


Figure 3.11 Coastal zone classification map of northern Qatar derived from visual interpretation of Landsat TM image band 1 dated 1987 (see also Table 3.2).

Unit	Area	Landform	Soil	Plant Community
1	Large	Carbonate sediments transport by long-shore current; originated from the northern tip of Qatar; they form many of today islands, beach-barriers, bars, spits, tidal mudflats and channels.	Skeletal debris from corals, algae and sea shells.	———
2	Medium	Reefs and other sources of carbonate sediment; the area is exposed to the full force of the dominant winds, resulting in high water turbulence which is beneficial to those carbonate producing organisms.	Skeletal debris from corals, algae and sea shells.	Seagrass
3	Medium	Accretion areas.	Skeletal debris from corals, algae and sea shells.	———
4	Large	Coral reef; rocky reef and sand bar occurring in the shallow sea water parallel to the shoreline.	Sand originally formed as skeletal debris from corals, algae and sea shells.	———
5	Large	Fine-grained carbonate sediment occurs in the lagoons or open sea, which are always below low tide. These sediments have a thickness of more than 8 m.	Mixtures of pelleted mud and silt-sized carbonate appear in predominantly gray colour and contains different amounts of winnowed skeletal grains and dolomite.	Seagrass in some areas such as the extreme north of Qatar.
6	Small	Intertidal zones: fine silts and calcareous sands, beach rocks, bed rocks, tidal channels, beach or bed rocks covered by sands.	Fine silts and calcareous sands.	Halophytic plants.
7	Small	Sheltered halophytic plants colonise the muddy sediments of the tidal flats, channels and intertidal areas.	Fine silts and calcareous sands appear in predominantly gray colour and contain different amounts of winnowed skeletal grains and dolomite.	*Avicennia marina* (mangroves), *Arthrocnemum glaucum, Juncus rigidus, Aeluropus* and *Stromatolites.*
8	Medium	Saline and gypsiferous sand and silt flats; a complicated tidal channel system; wide supratidal zones; evaporite crusts; polygonal patterns; brine-filled pools.	Fine silts and calcareous sands appear in predominantly gray colour and contain different amounts of winnowed skeletal grains and dolomite.	Some halophytic plants: *Arthrocnemum glaucum, Juncus rigidus, Aeluropus lagopoides* and *Stromatolites.*
9	Small	Scattered shallow, superficial depressions act as individual containment areas, receiving runoff water through shallow and poorly developed water channels.	Fine-grained silts and mud alluvium derived from the weathering and breakdown of the surface rocks. Accumulations average of 3 m on the floor of those depressions.	*Ziziphus nummularia, Cymbopogon parkeri, Acacia tortilis, Ehrenbergiana* and *Lycium shawii.*
10	Large	Beach-barriers; bars; spits; beach rocks; islands; sand banks; eolian sands which do not form dunes but rather thin widespread accumulations of calcareous sands with unique linear patterns that indicate the direction of the prevailing NW winds.	Calcareous sands with marine origin (skeletal debris from corals, algae, sea shells, etc.).	———
11	Large	Rocky and conglomerate hamada desert which is slightly elevated, gently sloping and covered by stones, gravel and eolian deposits.	Eolian sand	*Zygophyllum quatarense, Acacia tortilis* and *Lycium shawii.*
12	Small	Rus Formation exposures (Early Eocene) consists mainly of dolomitic limestone and chalk.	———	———

Table 3.2 A classification of the coastal zone of northern Qatar (Units refer to Figure 3.11).

CHAPTER 4

4. OIL POLLUTION AND THE ARABIAN GULF

4.1 INTRODUCTION

Oil pollution in the Arabian Gulf goes back to the beginning of the discovery and production of oil in the states surrounding the Gulf. Initially oil pollution was not a major problem and did not represent a threat to the Gulf or its ecosystem. However the world demand for oil increased, especially for oil from the Gulf. As a result, oil production in the Gulf nations increased dramatically and the Gulf became one of the world's busiest oil transport arteries through which more than half of the world's oil supply passes (Oostdam, 1980). With this increase the Gulf started suffering from oil pollution.

A further result of the dramatic increase in oil production, was that the countries surrounding the Gulf became among the fastest developing nations in the world. Populations in towns and cities along its coast have been growing dramatically. Other development such as industries, especially oil-related industries, and desalination plants have become concentrated along its coast. This development has also intensified environmental pressures in the Gulf region, and has increased the impactance of coastal environmental quality.

The Iraq-Iran war which broke out in September 1980 and the invasion of Kuwait by Iraq in August 1990, have further worsened the situation in the Gulf region. Very large oil spills were released into the sea of the region, and because of the wars attempted clean-ups were ineffective or impossible.

4.2 THE LOCATION AND PHYSICAL CHARACTERISTICS OF THE ARABIAN GULF

The Gulf extends between 24° to 30° north and 48° to 56° east. It occupies an area of 226,000 square kilometres and stretches 1000 kilometres from the northwest to the southeast. The Gulf is 300 kilometres at its widest and 56 kilometres at its narrowest in the Strait of Hormuz (Al-Amirah, 1985) (Figure 4.1). It is surrounded by eight countries (Iran, Iraq, Kuwait, Saudi Arabia, Bahrain, Qatar, United Arab Emirate , and Oman) (Figure 4.1) which are all considered major oil producers. Their oil fields, refineries and oil facilities are all concentrated along the Gulf shoreline.

The Gulf is considered to be a small, shallow and nearly landlocked sea. Its average depth is 35 metres. The deepest water is off the Iranian shore and the shallower water is off the Arabian shore. It is located in an arid region in which average temperature in the summer is about 35° and in the winter around 15°. The rate of evaporation is very high and the annual rainfall is very low. The river discharges from Shatt al Arab, at the northwestern end of the Gulf are very small and do not compensate the losses by evaporation. The only compensation for the water lost by high rates of evaporation comes from the net inflow from the Indian Ocean through the narrow Strait of Hormuz. This causes a system of counter-clockwise surface currents parallel to the Iranian side. Subsurface currents occur in the Arabian side as the dense water sinks and then flows out through the Strait of Hormuz (Figure 4.1) under the less dense incoming water (Neuman, 1979; Oostdam, 1980; Al-Amirah, 1985).

The high rate of evaporation, the low rate of annual rainfall, the low river discharge, and the slight exchange of water with the Indian Ocean make the Gulf water very salty. Salinity of the Arabian Gulf waters is about 40 parts per thousand and 70 parts per thousand in some shallow coastal areas that are exemplified by restricted bays and lagoons (Al-Amirah, 1985). These factors also decrease the Gulf's ability to flush itself and as a result any pollution discharged into the Gulf is likely to stay there and become concentrated.

4.3 THE MAJOR CAUSES OF OIL POLLUTION IN THE GULF

As it is mentioned earlier more than half the world's oil supply is pumped and shipped from the Arabian Gulf through the Strait of Hormuz. As a result oil spills and leaks have long been a problem for the countries surrounding the Gulf. For example, between 1965 and 1976 Kuwait recorded 109 oil spills, and during 1978 and 1979 there were 412 oil slicks in the Gulf and its approaches reported by tanker captains to the Japan Oceanographic Data Centre (JODC) (Oostdam, 1980; Al-Amirah, 1985). In spite of this there was no major action taken from the countries surrounding the Gulf to combat and control the increasing problem of sea water pollution caused by oil spills and leaks. The main reason behind this is the fact that these states lack the scientific structures to monitor and assess the oil spills and their impact on the Gulf ecosystem.

There are many sources of the oil that contribute to the sea water pollution in the Gulf such as refineries, local oil exploration and exploitation and routine handling of petroleum at ports. Contamination by oil could also originate from heavy maritime transport of oil through the region, as a result of the discharge of ballast water from tankers. The biggest source of oil pollution in the Gulf today comes from oil spills originating from war damaged wells and tankers.

4.3.1 Oil pollution from refineries discharges

As major oil producers, the countries surrounding the Gulf have established heavy petrochemical industries to diversify their economies. Today there are many petroleum refineries and petrochemical complexes. These industrial plants have been discharging thousands of tons of oil a year directly into the Gulf. Saudi Arabia's Ras Tunnura refinery, one of the largest refineries in the world, for example, discharges tons of oil a year directly into the Gulf. El Samra *et al.* (1986), measured the highest value of oil pollution (546.4 ppb) in the Gulf around the Ras Tunnura area.

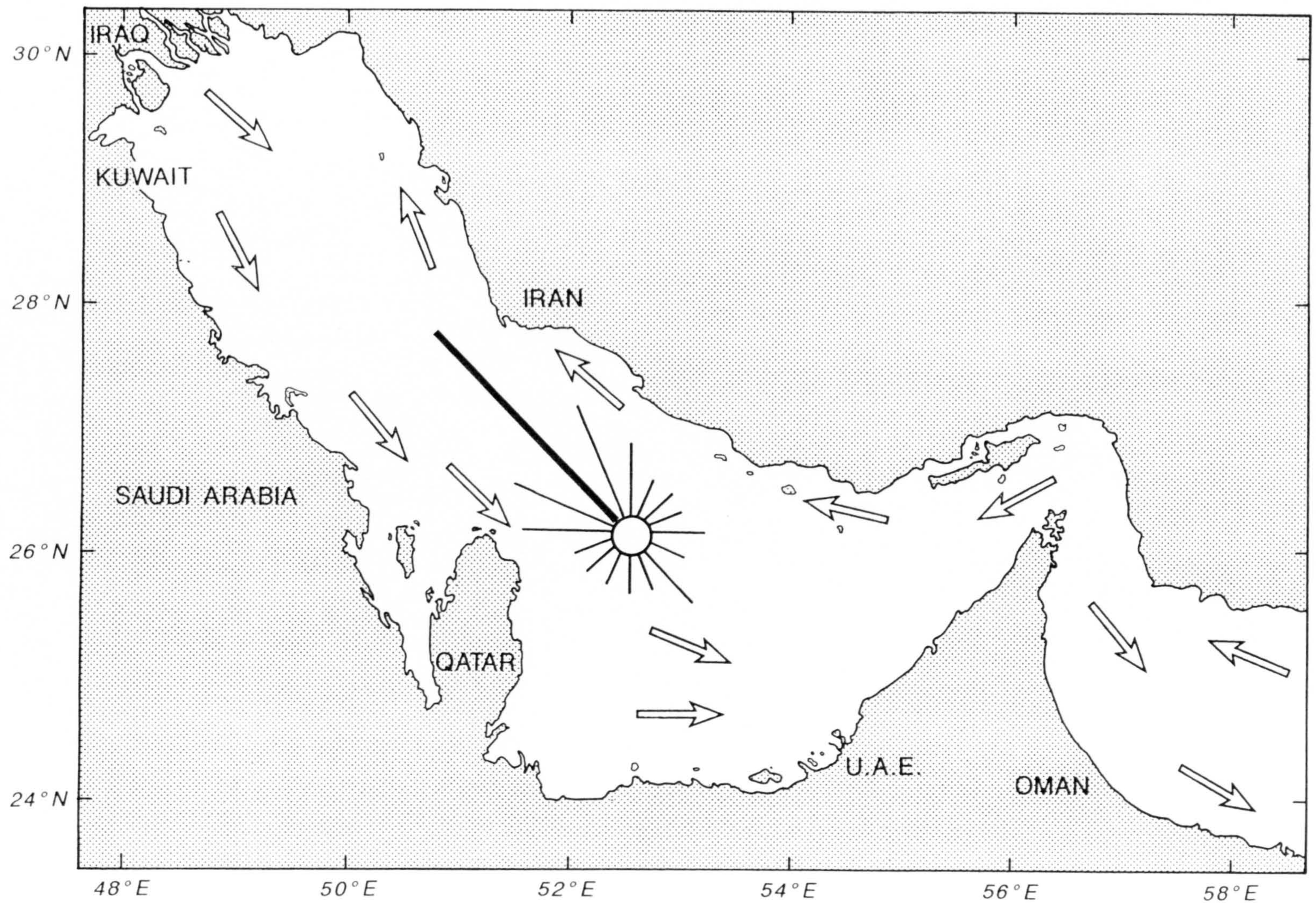


Figure 4.1 Predominant water currents and wind direction in the Arabian Gulf (Source: The Hydrographer of the Navy, 1967).

4.3.2 Oil pollution from offshore production and maritime transportation of crude oil

On the 20th of April 1970 during a stormy night a pipeline broke on land very near the northwestern shore of Tarut bay, on the eastern coast of Saudi Arabia (Spooner, 1970). 400 square kilometres of the very shallow bay received an estimated 100,000 barrels of crude oil. Furthermore, in December 1983 a Greek oil tanker sank in the Gulf waters east of Doha (eastern Qatar peninsula). The tanker was loaded with crude oil from the Umm Said oil terminal in the southeast of Qatar and was leaving the Gulf when the incident happened. No estimation of the amount of spilled oil in this incident was reported (El-Kassas, 1983). These are the pipeline and tankers incidents that occured in and near to the Qatar water.

However, about 60% of all oil carried by ships anywhere in the world is loaded in the Gulf, with around 100 oil tankers passing every day through the Straits of Hormuz to take on oil at Gulf terminals (Oostdam, 1980; Bryant, 1981). These tankers on their way to load up with oil cannot travel completely empty, because they would float too high in the water and be difficult to steer. To gain weight, they fill their tanks about half full with water. When they approach the oil terminals to load up with oil, they discharge this ballast water.

Ballast water is never clean because some oil from the previous load remains on the walls of the tanks (Bryant, 1981). The process of ballasting and deballasting contributes a great deal to the sea water pollution in the world's oceans in general and the Arabian Gulf in particular. According to Bryant (1981), Saudi Arabia's water, for example, receive nearly 400,000 tonnes of oil a year from deballasting.

According to El-Samra and El-Deeb (1988) and El-Samra (1989) researches on dissolved and dispersed hydrocarbons in the Arabian Gulf and their distribution during the period of 1984 to 1986, indicated that the oil-field and tanker routes are the main contributors of oil pollution in the Gulf. The research showed highest values of 40-500 ppb near the oil-field and intermediate values of ~22 ppb at stations located in the tanker routes. Furthermore, the research indicated that offshore oil fields can justifiably be considered as fixed-point source of oil pollution (hot spots) in the Gulf. These measurements agreed with the predicted model by Neuman (1979). The model showed the circulation pattern and potential risk of oil pollution in the Arabian Gulf (Figure 4.2). Predicted areas of high risk were found to be areas of high concentrations in the studies.

El-Samra *et al.* (1986) through their research of measuring dissolved petroleum hydrocarbon in northwestern Arabian Gulf indicated that high concentrations were measured in seawater off Kuwait, Saudi Arabia and Qatar. Seawater off the northern coasts of Qatar showed higher levels of concentrations than other parts of the Qatari waters. This is due to the water circulation prevailing in the Gulf which directs or steers polluted coastal waters of Saudi Arabia in a southward direction into the Qatari coastal area. This was also indicated by Aboul Dahab (1994) and Aboul Dahab and Al-Madfa (1993) that the possible sources of oil on the Qatari coasts are mainly external on the western coast and local on the eastern side.

4.3.3 Oil spills from war damaged oil wells and tankers

During the Iraq-Iran war in 1980, many tankers were attacked and oil rigs and refineries destroyed. Iraq used attacks against Iran's oil rigs, refineries, tankers and oil terminals to destroy its economy and to force Iran to accept a general cease-fire in the war. On the other hand Iran rejected all cease-fire requests because it did not want to be forced by Iraq into a cease-fire, and at the same time insisting that Iraq was to blame for the war. Iran insists that Iraq should pay a compensation to Iran for what was lost in the war.

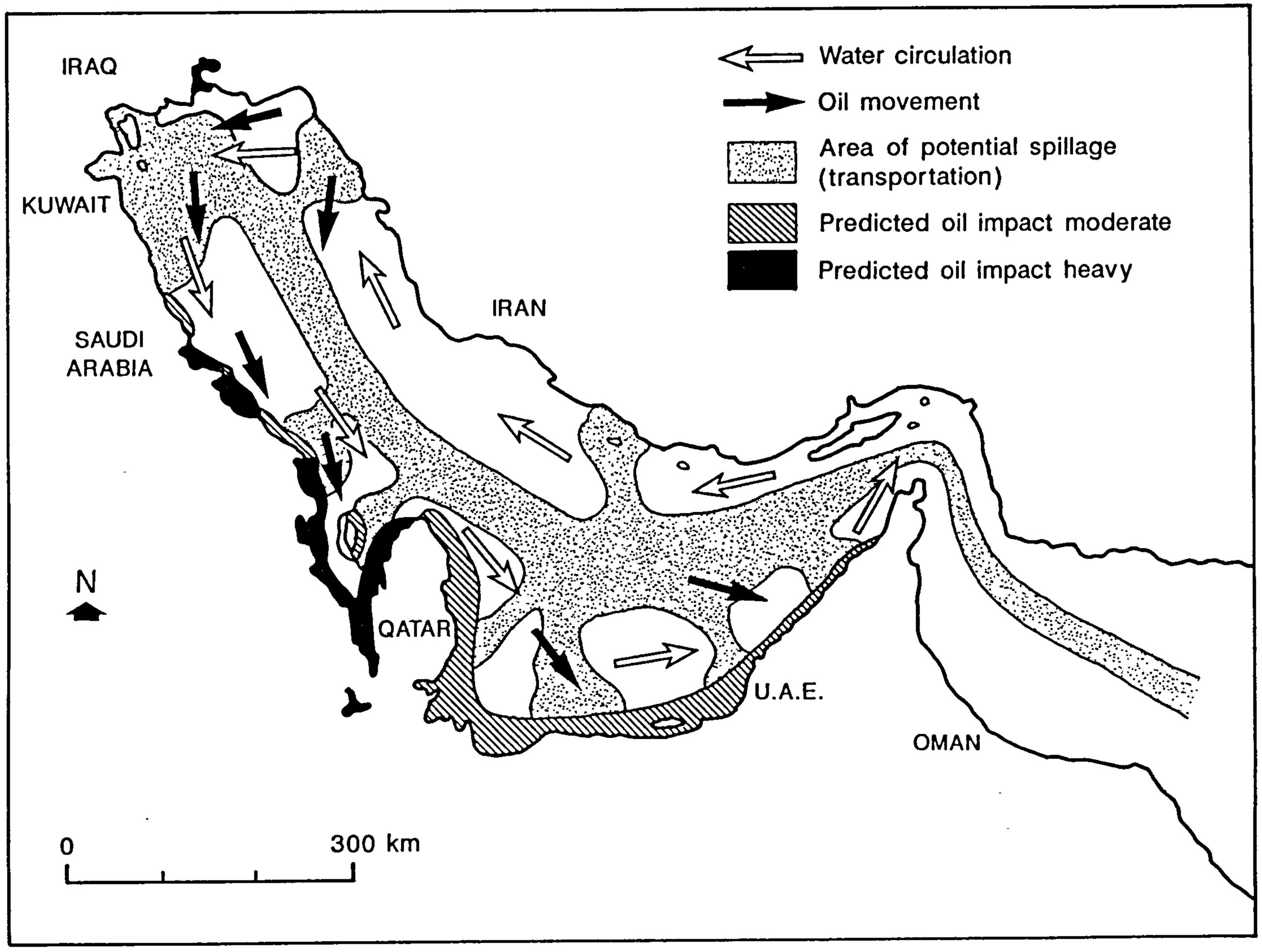


Figure 4.2 Predicted sources, movement and coastline impact of oil spill in the Arabian Gulf (Source: Neuman, 1979; El-Samra and El-Deeb, 1988).

In March of 1983, Iraq destroyed the Iranian Nowruz oil field in the north end of the Gulf, and a few weeks later more rigs in the same area were destroyed. The well blow-out caused an estimated spill of 2,000 to 4,000 barrels of heavy crude oil per day. The Iraqi attack was resumed in April of the same year in the Ardeshire oil field 53 km kilometres south of Nowruz oil field. It was difficult to conduct aerial surveillance over the source of spills due to the war, but some sources have estimated the damage as up to ten wells spilling 5,000-7,000 barrels of oil daily into the Gulf (Fayad, 1986; Al-Amirah, 1985).

In August 1990, almost seven years after destroying Nowruz oil field, Iraq invaded Kuwait. During the early days of the Gulf war (between January 19 and 28 1991), Iraq ordered a series of oil discharges from vessels in Kuwait and Iraq in order to deter an amphibious landing of coalition forces. Oil was released from three Iraqi tankers located at Kuwait's port of Mina al Ahmadi and leakage from the Mina al Ahmadi Sea Island terminal mooring area. Sporadic discharges, in addition, occurred from these and other sources through all June 1991.

An estimated 6 to 8 million barrels of oil were spilled into the Gulf water. It was immediately apparent that this would be one of the largest oil spills in history. Additional atmospheric fallout from the destroyed wells in Kuwait (749 oil wells) gradually introduced a considerable quantity of oil in the form of small oil droplets and oil soot (Rodstein and Ott, 1992; Office of the Chief Scientist, NOAA, 1993; International Maritime Organisation (IMO), 1993).

The Gulf winds and currents moved the main body of the slick southward along the Saudi Arabian coast and repeatedly drove it onto shore and then back out to the sea. As a result, 770 km of the eastern Saudi Arabia coasts were polluted. The most heavily polluted areas were the lagoons and bays north of Abu Ali island up to Ras al Saffaniya (Figure 4.3). Abu Ali island blocked the southern progression of the slick and as the oil continued to move into the area, it backed up into the farthest recesses of the embayments north of Abu Ali island.

In addition, the coastal geometry of the area is such that it provides the natural harbour for any aquatic pollutants such as oil spills (Rodstein and Ott, 1992; Al-Gunaim *et al.*, 1992; Office of the Chief Scientist, NOAA, 1993). The winds and currents of the Arabian Gulf kept the slick offshore Kuwait coastline. Later, when ships sank in the north of the Gulf, oil began to seep, affecting the southern Kuwait shoreline.

As a normal phase in the weathering of oil on surface waters, large offshore patches of sheen and streamers began to break up in early March from the main spill. Spreading, evaporation, dissolution, and emulsification are the physical and chemical processes that are termed weathering, the product of which is weathered oil. In the Arabian Gulf, as in most oil spills, the weathered oil formed thick and dark streamers of chocolate-mousse (water-in-oil emulsion) surrounded by patches of sheen. The sheen emanates from the streamer and they moved together on the water surface. As the streamers shrank less sheen emanated and tar balls were formed from the mousse. As a result sheen patches also began to break up (Oostdam, 1980; Rodstein and Ott, 1992; Al-Gunaim *et al.*, 1992; Aboul Dahab, 1994). All these different types of weathered oil were moved by the counter-clockwise water currents in the Arabian Gulf and the prevailing north-westerly winds (Figure 4.1) toward Bahrain and Qatar. The pollution resulting from this event is prominent amongst the impacts assessed below.

Horn in 1977 mentioned that Arabian Gulf has the advantage of high solar radiation to enhance photolysis, evaporation, solution and bacterial degradation, so that even major oil spills tend to disappear surprisingly rapidly. This can be true if the oil spill remains offshore and far away from the coastal area, which was not the case in the Arabian Gulf. Reports from the last two major oil spills (Nowruz and the Gulf war oil spills) showed that the drift of spilled oil in the Gulf is largely determined by the counter-clockwise water currents and the prevailing north-westerly winds of the Gulf (Figures 4.1 and 4.2). These tend to deposit a large amount of the oil in the Gulf's sensitive subtidal and intertidal zones.

According to the Office of the Chief Scientist, NOAA, Washington (1993) which examined the last spilled oil in the Gulf in 1991:

> "About three million barrels of the spilled oil were estimated to have evaporated within the first five days of the initial discharge. One and a half million barrels of floating oil were recovered by Saudi Arabia authorities, leaving 1.5 to 2.5 million barrels which are believed to have been dispersed in shallow water or deposited in intertidal and subtidal sediments."
>
> (Office of the Chief Scientist, 1993).

4.4 THE IMPACTS OF OIL POLLUTION

The marine environment in the northwestern part of the Arabian Gulf is more highly polluted than that of other marine environments such as the Suez Canal, the Mediterranean Sea and the Gulf of Mexico (El-Samra *et al.*, 1986). This is because the Gulf is a relatively shallow and isolated sea, and winds and inflow currents are the main driving force for its circulation. Furthermore, the southwestern side of the Gulf is characterised by shallow water, with very wide intertidal zones commonly greater than one kilometre wide, and sometimes up to several kilometres.

The coastline presents an uneven outline with extensive system of bays and lagoons, sabkhahs, salt marshes, seagrass beds, sandy beaches, coral reefs, sand banks, and offshore sand islands. Detailed study of these various types of coastal environment for the northern half of Qatar peninsula are discussed in Chapter 3. The Qatar peninsula is part of the southwestern side of the Arabian Gulf and represents an example of its sensitive and shallow coastal environments, which are all along the southwestern side of the Arabian Gulf.

Some of these habitats especially the offshore sand islands, are found to provide important nesting grounds for endangered sea turtle species and rookeries for important migrating birds. The gentle slopes and large tidal ranges provide an extensive source of food for many marine life. Therefore, any oil pollution in these feeding and breeding grounds has the potential for deleteriously impacting on populations of these animals that inhabit areas far removed from the Arabian Gulf (IMO, 1993). Besides this, oil pollution can threaten several desalination plants along the southwestern part of the Gulf and, therefore, the fresh water supply of the area.

According to Al-Amirah (1985), more than 100 sea turtles have been found dead on the Saudi coast as a result of the Nowruz oil spill. During the day, the heat melts the oil tar (resulted from the oil spill) on the coast creating tar pools, which then entrap turtles coming onto the shore and prohibit passage to the sea. During the oil spill, Saudi Arabia government prohibited fishing in the Arabian Gulf fearing that the fish and shrimp from the Gulf may be hazardous for human consumption. Dugongs in the Arabian Gulf in the Gulf of Salwa between Qatar and Saudi Arabia are estimated to be only 50 individuals; 31 were found killed on the Saudi shorelines as a result of oil pollution from the Nowruz oil spill.

The Gulf war oil spills in January 1991 made the situation of oil pollution in the southwestern side of the Gulf worse and had a very severe impact on these habitats. For example, the entire shoreline of Karan island (Figure 4.3), off the east coast of Saudi Arabia, was found to be oiled. The island is known to be the most important nesting site for green turtle in the Arabian Gulf. A tar mat about 35 cm deep and 30 m wide was found covering the nesting beach of the island (IMO, 1993).

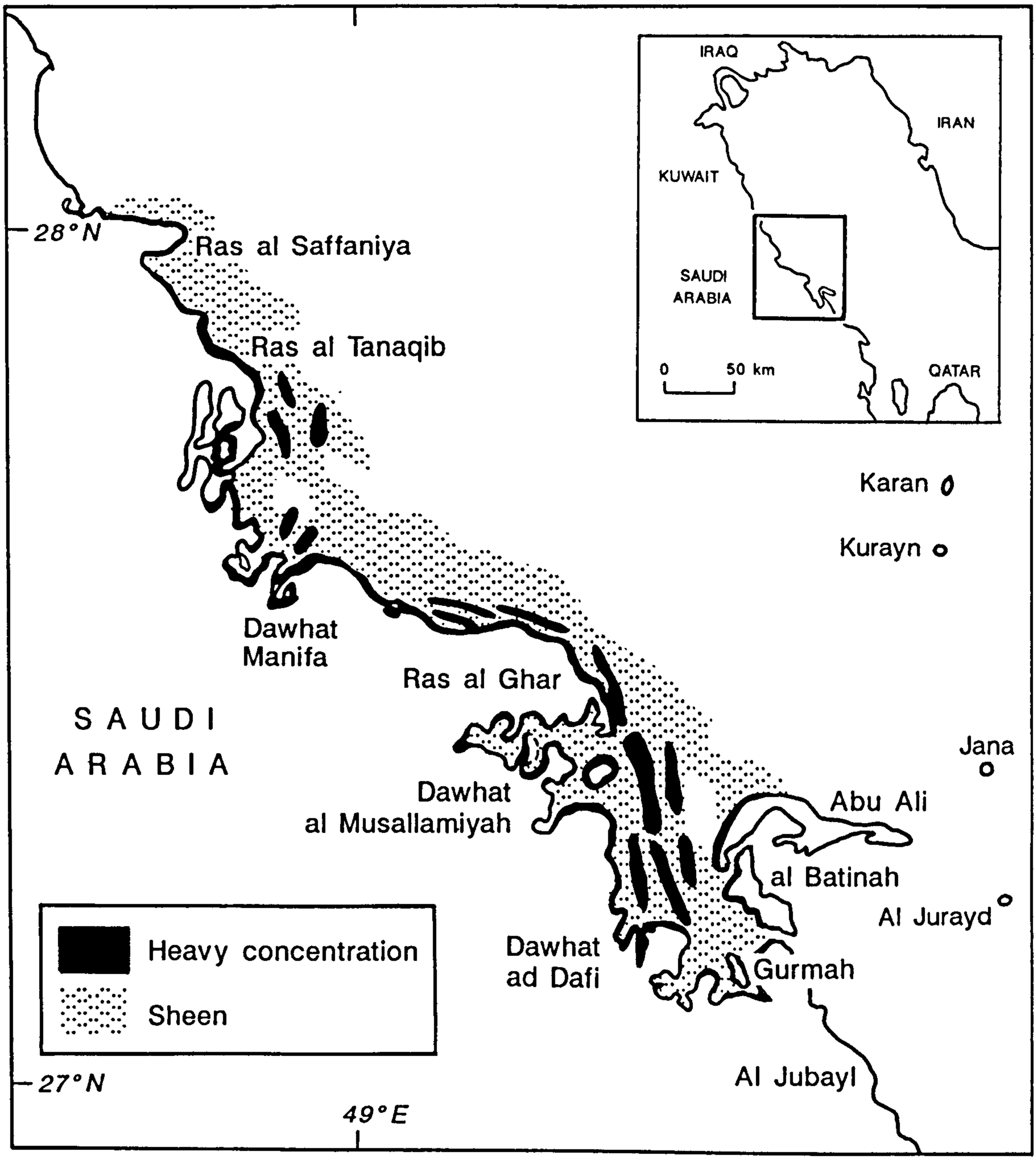


Figure 4.3 The most heavily polluted lagoons and bays in the eastern coast of Saudi Arabia from the Gulf War oil spills in 1991
(Source: Rodstein and Ott, 1992).

The south end of Dawhat ad Dafi (Figure 4.3), Gurmah island supported the largest natural stand of mangroves on the eastern coast of Saudi Arabia. During this spill the island was severely oiled. Many plants were oiled up to one meter high. Furthermore, to the north of Dawhat ad Dafi several miles of salt marsh were oiled in the Musallamiyah bay. The bay was holding a large quantity of free floating surface oil, which was absorbed into the soil and the algal mat. Oiled vegetation was observed along much of the affected Saudi Arabian coastline. It was recognised that the marine and coastal environment of the eastern coast of Saudi Arabia received the main impact of the spill (IMO, 1993).

In addition, impacts were also recognised in the marine and coastal environment of Bahrain and Qatar. In Qatar for example, the impact of the spill was obvious and heavy, covering the northern and northwestern intertidal zones and beaches with tar mats (Figure 4.4). The highest levels of oil were found in the sandy sediment of northwestern Qatar (Aboul Dahab and Al-Madfa, 1993; Aboul Dahab, 1994).

The entire shoreline was covered with oil ranging in thickness from a millimetre up to several centimetres. In some places, the oil did completely cover the sand, but heavily mixed with it. Several layers of oil can be distinguished which suggests that these shores have been covered by oil several times (Aboul Dahab, 1994). The entire coastal zone area of north and northwest Qatar is known to be exposed to the high energy of the predominant winds and surface currents. The area, in addition, is characterised by shoals intersected with reefs extending for kilometres offshore. By adhering to suspended sediments of greater density, oil sank to bottom water and sediments (Figure 4.5) causing high levels of pollution at bottom layers. As far offshore as the eye can see the bottom appeared to be covered with oil tar.

Figure 4.4 Weathered tar mat on the northern Qatar intertidal zone from the Gulf War oil spills in 1991.

Figure 4.5 Weathered tar mat on the bottom water sediments offshore Ras Rakan island, northern Qatar from the Gulf War oil spills in 1991.

4.5 POLITICAL RESPONSE TO OIL POLLUTION IN THE GULF

Recently the steadily growing pollution of the Gulf has became more and more apparent to the public and authorities in the Gulf countries. Many attempts have been made to control this problem. For example, in Kuwait from 15-23 April 1978, the eight countries surroundings the Gulf signed a regional project to control pollution and promote sustainable development in the Gulf. The project was called the Kuwait Action Plan (KAP). It had been developed by the United Nations system, under United Nations Environment Programme (UNEP) coordination. Initial project activities were scheduled to begin in early 1979 and continue for two years (Neuman, 1979). The activities were postponed because of the Iraq-Iran war.

The Nowruz oil spill in 1983 raised many questions and concerns among the agencies and authorities responsible for environmental protection. For example, the Regional Organisation of the Protection of the Marine Environment (ROPME) conducted many meetings in Kuwait and Bahrain among the ministers of health and experts from the Gulf nations to reach a political solution to cap the Nowruz well, and design a plan for a clean-up operation. The ROPME did not succeed, because Iraq and Iran did not agree on a cease-fire to the war. As a result each country started conducting its own monitoring programs and clean-up operations to prevent the potential risk from oil spills.

In late January 1991, during the Gulf war oil spills, the situation of combating the enormous oil slick in the Gulf was different. The whole world became aware that millions barrels of crude oil were being released into the Gulf and no one government or oil industry organisation would had the capabilities to combat it. Therefore, it was recognised that international assistance and cooperation would be very necessary.

On November 30, 1990, at a conference held in London, Member Governments of the IMO adopted the International Convention on Oil Pollution Preparedness, Response and Co-operation (OPRC Convention) and associated resolutions. The result of the OPRC Convention was to develop an international framework for co-operation in combating major oil pollution incidents. The oil spill in the Gulf appeared to be one of the largest oil spills in history and posed a very serious environmental threat to the marine and coastal resources of the region.

The Secretary-General of IMO called for the establishment of the Persian Gulf Oil Pollution Disaster Fund on 15 March 1991. The Fund was $ 5,721,409 established through the contributions of several Member Governments of the IMO. Several projects of oil spill clean-up operation were carried out under the Fund to mitigate harmful impacts to environmentally sensitive coastline areas (IMO, 1993).

In addition, and soon after the 1991 Gulf war, many studies were conducted in the Gulf by the NOAA research vessel Mt. Mitchell. The researches were focused on the environmental aftermath of the oil spills. They included studies of shoreline and near-shore regions (the most heavily impacted areas), regional circulation and sedimentation, coral reef, and seafood quality. 142 scientists representing 15 nations were aboard the vessel for 100-day expedition in the Arabian Gulf. The Mt. Mitchell expedition provided an opportunity to focus a broad range of scientific talent on an ecological problem of enormous consequence. However, the full significance of the expedition may not be known for some time (Office of the Chief Scientist, 1993).

4.6 CONCLUSION

In conclusion, this chapter has discussed the various sources of oil pollution in the Arabian Gulf. Oil pollution appears likely to be continue as a major threat to the coastal environment as long as there is a global reliance on petroleum products. Oil exploitation is still and will continue to be the main source of income for all the states surrounding the Gulf. Most new industrial developments in the Gulf are also oil-related and concentrated along the coast, which have intensified more environmental pressures in the coastal zone of the Gulf. The need for stronger coordinated environmental programs among the Gulf States appears to be essential to preserve the Arabian Gulf environment.

Protection of the fragile coastal zone environment in the Arabian Gulf is very important. The protection needs first the knowledge of the different habitat environments that exist in the coastal zone areas. Since these information are not available for most of the coastal Gulf states. Sensitivity mapping of coastal zone habitats, therefore, is highly essential and required for the protection and better management of those habitats. Detail on sensitivity mapping by using modern technologies such as remote sensing and geographic information system will be discussed in the following chapters of this thesis.

CHAPTER 5

5. THE ROLE OF REMOTE SENSING IN COASTAL ZONE SENSITIVITY MAPPING OF QATAR

5.1 INTRODUCTION

Remote sensing provides the only practical means of mapping and monitoring changes over large areas of the Earth's surface and the technique is well-suited to arid and semi-arid areas of the world where the low cloud cover allows the use of sensors operating in the optical region. Methods to analyse such data have been refined over the last 25 years through world-wide experience with sensors such as the Landsat MSS and TM, and a country such as Qatar can therefore adopt this technology, secure in the knowledge that the basic interactions and processes are reasonably well understood. The coastal zone classification map presented in Figure 3.11 is an example of this use of appropriate remote sensing technology; it was produced by visual interpretation of the Landsat TM image shown in Figure 5.1 and it succeeds in showing the main coastal environments of interest. However, for the purpose of oil spill response, it is necessary to produce a much more detailed map, as many of the areas which are of greatest ecological interest, such as mangroves, salt marshes and tidal flats, are small and scattered along the coastline. Experience with aerial photography, and knowledge of the area on the ground, suggested that a nominal ground resolution of 2 metres would be necessary for the task. If we assume that the average width of 'the coastal zone' is 5 km, and the length of the coastline of Qatar is approximately 500 km, the enormity of the remote sensing task becomes clear - and the impossibility of achieving it using conventional ground survey methods.

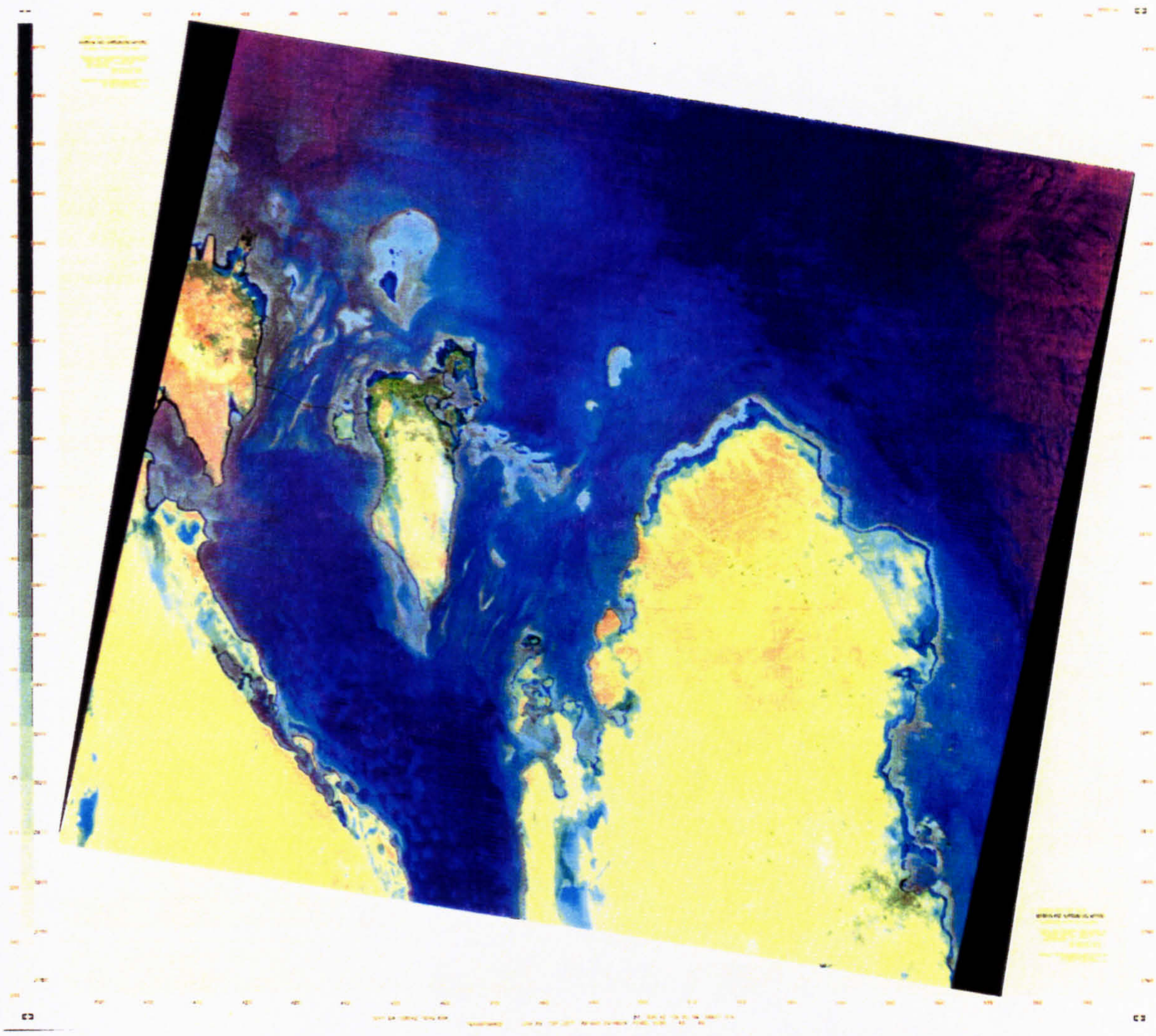


Figure 5.1 One full scene of Landsat Thematic Mapper (TM) covering the northern half of Qatar and the surrounding waters and islands.

The rest of this chapter describes the research undertaken to meet this challenge, and, ultimately, overcome it. Throughout the research, the guiding principle has been the development of techniques and approaches to the problem which will be capable of application to the entire coastline of Qatar, which can be implemented locally, and which will provide the information which is so urgently needed to manage the response to future oil spills in the coastal zone. In undertaking this research I have been aware throughout of the need to balance technical innovation in remote sensing methods with the practical implementation of that research to provide urgently needed environmental information, and this has led, at times, to potentially interesting avenues of research being curtailed when it became clear that the methods involved were not robust enough to be used operationally in Qatar.

The overall aim of this Chapter is therefore *to investigate a number of possible methods of producing high spatial resolution land cover maps of the coastline of Qatar using remote sensing, and to identify the* ***most appropriate*** *methodology for use in an operational coastal zone management system.*

5.2 THE HISTORY OF REMOTE SENSING IN QATAR

Remote sensing application in Qatar dates back to 1977 when Grolier mapped surficial geologic structures and deposits using visual interpretation of Landsat MSS from January 1973. Many remote sensing studies following Grolier also mapped surficial geology by using visual interpretation of Landsat imagery and aerial photographs. Very few were directed toward coastal zone applications. This is probably due to the applied focus in Qatar. Remote sensing in Qatar was first initiated by geologists whose interests were in the use of remote sensing for mapping surficial structures and deposits for the interpretation and understanding of subsurface geology. These works include Yehia and Harhash (1982) who also used visual interpretation of Landsat MSS to update the hydrographic charts of Qatar. They found that the images correlated with the geophysical resistivity maps of the peninsula, and both showed the presence of two main hydrogeological provinces. Yehia *et al.* (1982) investigated the major surface structures, topography and hydrology by using the same Landsat MSS images of the previous study. A geological structural map (scale 1:250,000) and a map of 850 topographic depressions were created, revealing information on the presence of fresh water bodies.

A research project was carried out in 1992 between the Scientific and Applied Research Centre (SARC), Qatar, and the UK National Remote Sensing Centre Limited (NRSCL) to use Landsat TM data for bathymetric mapping of the sea water around Qatar peninsula. NRSCL and the Qatar Department of Agriculture and Water Resources surveyed the whole coastal zone of Qatar peninsula using a Daedalus AADS-1268 airborne scanner in order to detect fresh water springs in the Gulf.

Other geological or geophysical studies to have used remote sensing in Qatar include those by Yahia (1983a; 1983b) and Hunting Geology and Geophysics, Ltd. (1983a; 1983b). Ashour and El-Kassas (1984a) used MSS images together with aerial photographs for the interpretation of the common aeolian features in the peninsula, while Ashour and El-Kassas (1984b) used MSS imagery for geomorphological mapping. El-Kassas and Ashour (1990) used Landsat MSS images for lineaments analysis.

Finally, El-Kassas *et al.* (1985) ; Noweir and El-Kassas (1988) ; Akbar (1989) ; Khamis (1989) ; Khamis *et al.* (1990) ; Akbar *et al.* (1990) and Akbar (1995) have all completed similar studies and shown the immense value of remote sensing for geological and geomorphological survey in Qatar.

However, the roots of this thesis are found not in the geological and geomorphological work listed above, but in the response to the 1991 Gulf War, and particularly in the environmental impacts of the major oil spills associated with the conflict. The events of the Gulf War highlighted the lack of information on the coastal zone of many Gulf states, and Qatar was no exception. In response to this, the entire coastline of Qatar was surveyed during April-May 1991 using an advanced pushbroom multispectral sensor developed by the Canadian Centre for Remote Sensing as part of an aid package negotiated between the Canadian government and the state of Qatar. The reminder of this Chapter describes my attempt to create from this enormous, unstructured data set both an archive of information which will be of lasting value to my country and a rationale for any similar data acquisition in the future.

5.3 DESCRIPTION OF THE AIRBORNE MEIS SENSOR USED FOR MAPPING THE COASTAL ZONE OF QATAR

In the mid-1980's the Canadian Centre for Remote Sensing developed an innovative optical wavelength airborne sensor, primarily for forestry applications, called the Multi-detector Electro-optical Imaging Scanner (MEIS) (Figure 5.2). The sensor was innovative in several ways. First, it was a pushbroom system, meaning that there was no scanning assembly, which allowed the detectors to have a long dwell time, resulting in a high signal-to-noise ratio. Second, the wavelengths sensed were determined by removable filters, which, because of the high signal-to-noise ratio, could be set to very narrow bandwidths, allowing features such as red edge shifts in vegetation to be detected. Third, the sensor was designed to be flown from a light aircraft at relatively low altitudes, resulting in images of very high spatial resolution (e.g. 50 cm) - ideal for studies of tree crowns.

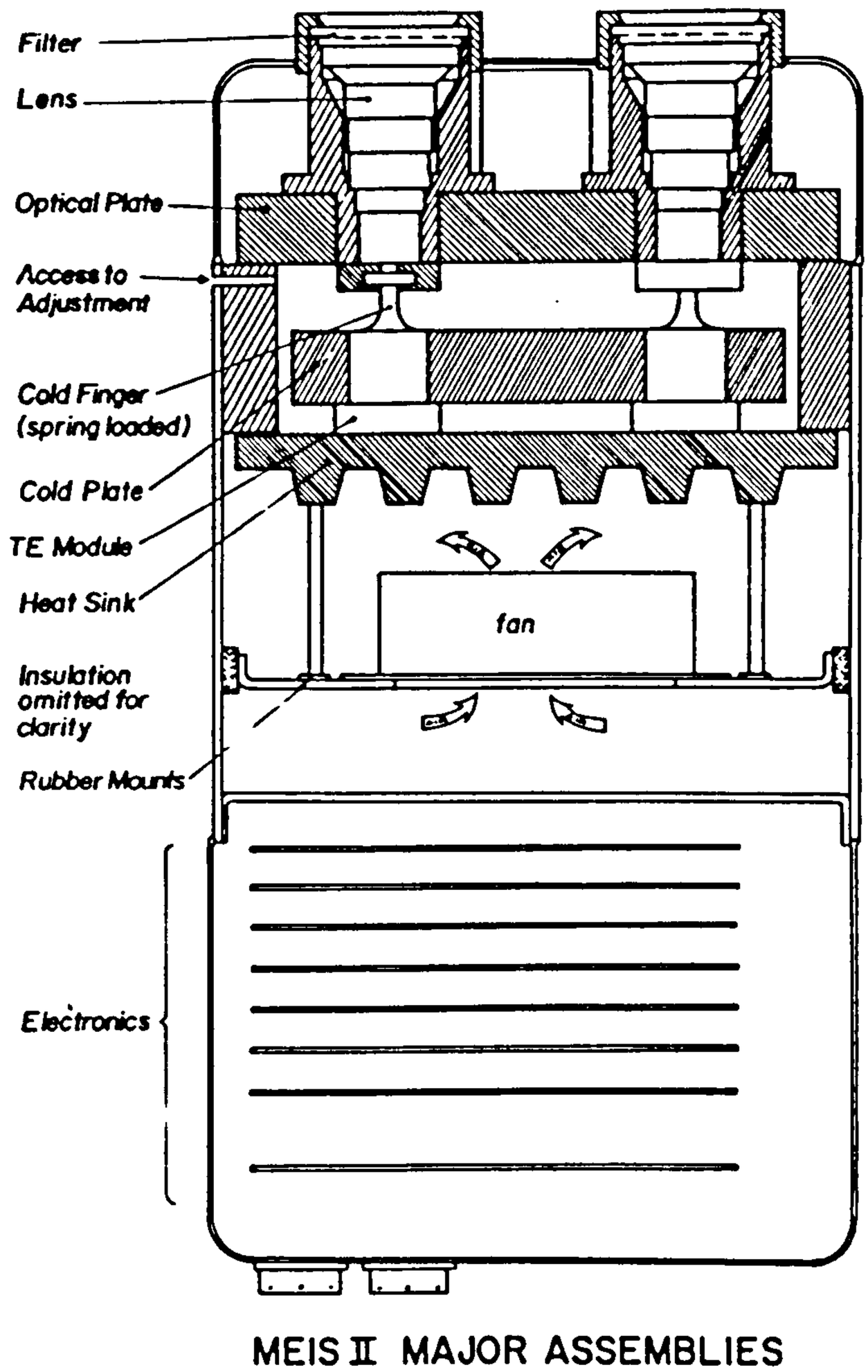


Figure 5.2 The high-resolution MEIS (Multi-detector Electro-optical Imaging Scanner (Source: McColl *et al.*, 1983).

MEIS is a pushboom imager configured using independent spectrally filtered, linear array detectors (McColl *et al.*, 1983 and 1984 ; Till *et al.*, 1986). The MEIS sensor used in Qatar had eight optical channels covering the visible and near-infrared parts of the electromagnetic spectrum (390 to 1100 nm) (Table 5.1). The bandwidths used were broader than is normal with MEIS, as it was more important to achieve a high signal-to-noise ratio than discriminate narrow spectral features. Thirty hours of data acquisition were performed during the mission by Innotec Aviation, Canada, using a Falcon 20 aircraft. A total of approximately 65 flight lines, each an average of forty kilometres long were acquired for the whole coastal zone of Qatar. The flying height of the aircraft was nominally 10000 feet, resulting in a nominal ground resolution at nadir of 2 metres.

Central wavelength (nm)	Mean bandwidth	Band limits (nm)	MEIS band designation	E.M. spectrum equivalent
449	30.6	464-489	7	Blue
518	24.0	506-530	6	Green
549	31.9	533-564	8	Green
596	35.3	579-614	5	Light red
640	37.0	622-659	4	Red
675	39.5	655-695	2	Deep red
750	32.3	734-766	1	Short IR
874	54.5	846-901	3	Short IR

Table 5.1. Description of MEIS sensor bands (Source: Prevost and Pouliot , 1991b).

5.3.1 Geometric correction of the multispectral MEIS imagery

Imagery acquired by the MEIS sensor is raw digital data which contains some geometric distortions introduced by the aircraft that carried the MEIS sensor during the time of the survey. They are introduced to the raw data by the motion of the aircraft, for example changes in the velocity of the aircraft, altitude of the aircraft, and attitude of the aircraft such as pitch, roll and yaw. In addition, the orientation of the scanned lines is not always north and the overall shape of the image is a long narrow strip which is difficult to display in the computer screen (Prevost and Poulit, 1991a and 1991b).

Therefore, the data were geometrically corrected after the flights. The CCRS in Canada has developed a comprehensive geometric correction software package operating on a minicomputer to overcome these distortions while keeping all the intrinsic radiometric value of the data. The software uses parameters computed by the aircraft Inertial Navigation System (INS) during the recording of the MEIS imagery onboard the aircraft.

When the MEIS imagery is recorded onboard the aircraft, the recording system also records the INS information along with a time tag. In addition, the time tag is also recorded with the MEIS imagery. Therefore, by using this time tag as a relational reference between the two systems (the navigation system and the acquisition system) it is possible to find the attitude of the aircraft at the time of acquisition of each line of data (Prevost and Pouliot, 1991a; Gibson *et al.*, 1987). The software then reads each line of MEIS data in all eight channels and geometrically adjusts the pixels of the line according to the corresponding information of the Inertial Navigation System (Prevost and Pouliot, 1991a).

5.3.2 Geocoding of the MEIS imagery

Geometric correction as discussed above using only airborne navigation data does not correct for the errors introduced by the aircraft position because these positional errors are not recorded by the INS (Till *et al.*, 1987; Prevost and Pouliot, 1991a). Therefore, a least squares solution using ground control points (GCP) was required to generate a platform error free and geocoded data set. A series of ground control points were acquired from published maps and matched on the display screen with their corresponding MEIS image pixels. The matched points were input into the geometric correction process to generate a new geocoded MEIS image using nearest neighbour resampling. Where the coordinates of each pixel in the MEIS image are transformed from the image coordinate system to a local geographical system and resamples the data to a convenient map projection grid such as Transverse Mercator (Prevost and Puliot, 1991a; Surveys, Mapping and Remote Sensing Sector, 1992).

5.3.3 Mosaicking of adjacent flight lines and construction of rectangular mosaic blocks of MEIS data

The previous two processes corrected for the geometric distortions introduced by the platform and also aligned the image data with the map grid, but the data were still in long sinuous strips and therefore not really suitable for creating rectangular map sheets from. It was therefore decided to request the data in mosaicked form, and the coastline of Qatar was divided up into 233 5 km x 5 km tiles (Figure 5.3). Each tile comprised a 5 km x 5 km geocoded mosaic of all eight MEIS bands, typically from five to seven flight lines, and each one was provided on a separate 8 mm tape (Surveys, Mapping and Remote Sensing Sector, 1992). Each tile comprised 2500 lines x 2500 pixels x 8 bands, resulting in a file size of 50 Mb per tile, or approximately 11 Gigabytes for the complete data set.

In addition, groups of four mosaics were merged to cover an area of 10 km by 10 km for seven selected sites in order to illustrate merging capabilities of geocoded data (Surveys, Mapping and Remote Sensing Sector, 1992). Two of these merged mosaics are used in the present study covering the northeast (mangrove forest) and north Qatar. The file size of each merged mosaic was therefore 200 Mb, and in the early stages of this research this greatly exceeded the storage capacity of any of the image processing systems which were available, either in Qatar or at the University of Southampton.

Whilst it is clear that handling this volume of data will present huge problems, especially on a small PC-based image processor, the potential benefits of such data can be seen immediately when an example data set is viewed. Figure 5.4 shows part of one of the tiles covering an area within Doha, the capital city of Qatar. The details of individual aeroplanes on the runway of Doha airport are clearly visible, and there is a wealth of information shown in the coastal zone and offshore.

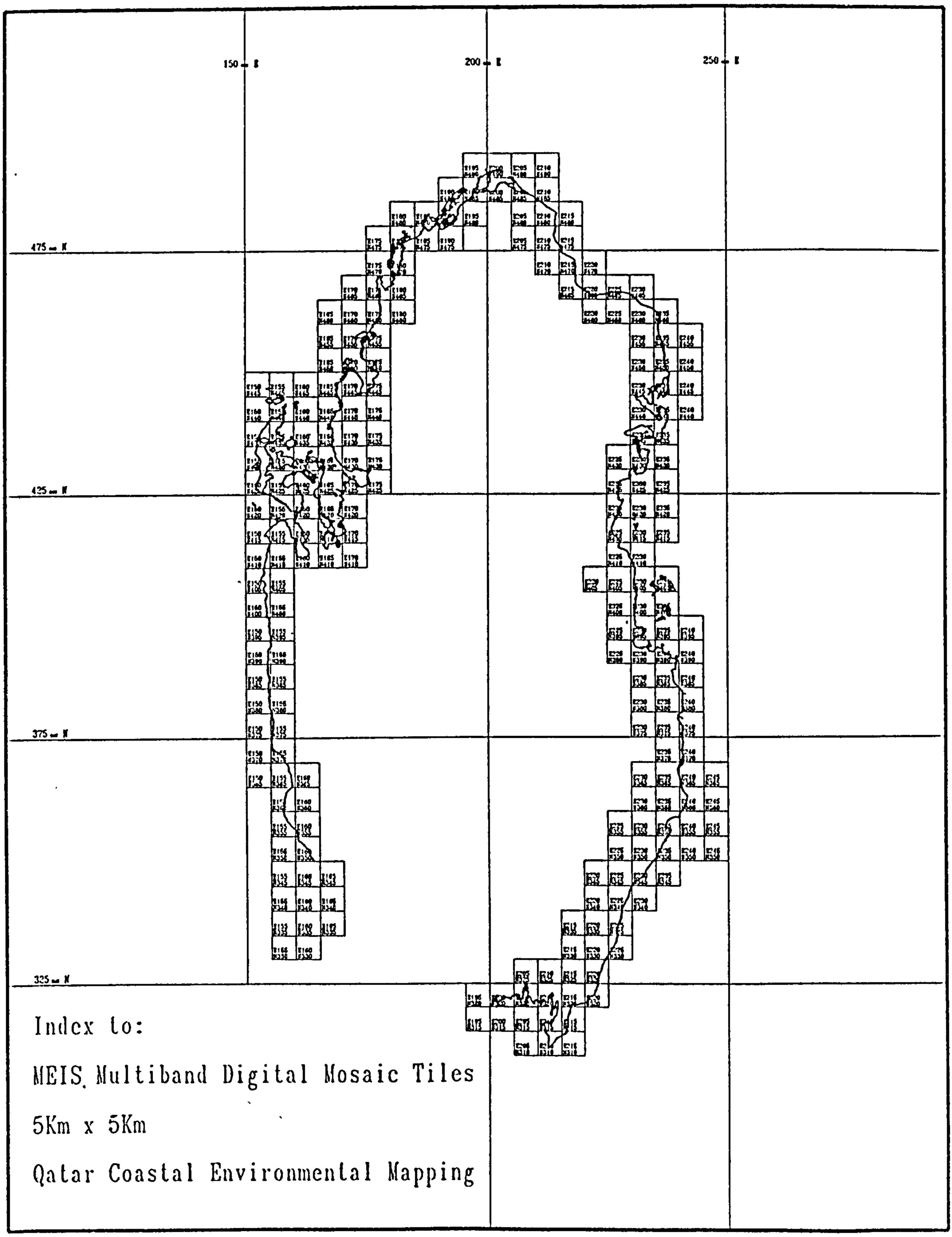


Figure 5.3 Location map of the 5 km x 5 km MEIS digital mosaic tiles.
(Source: Surveys, Mapping and Remote Sensing Sector, Canada, 1992).

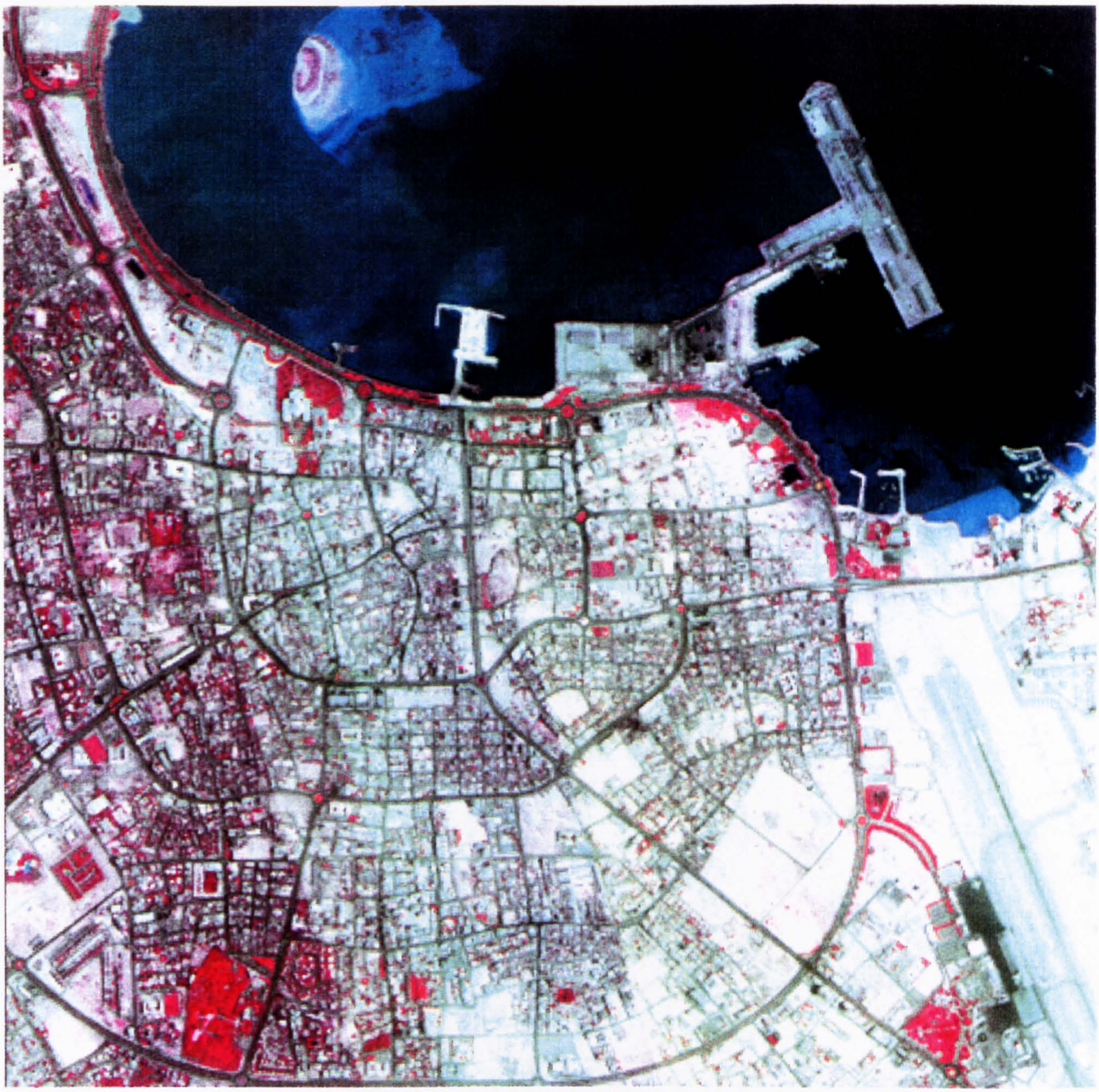


Figure 5.4 Example of the high spatial resolution airborne MEIS data covering the coastal capital city Doha, east of Qatar.

5.4 PRELIMINARY EVALUATION OF THE AIRBORNE MEIS DATA SET

It quickly became apparent that the MEIS data set as provided suffered from a number of problems. First, the sheer volume of data meant that it was exceptionally difficult to store, display, analyse and print any complete tiles in the early stages of the research. For example, in 1993 the hard disk storage available on-line was 90 Mb - enough for the raw data from one tile, but insufficient to store a second, processed version, which meant that even creating a colour composite was a challenge and an 8-band classification was impossible. Reading a 200 Mb merged mosaic from its 8 mm tape required a very convoluted process involving several PC and mainframe computer systems and could take several days in the early stages. Figure 5.5 shows a visual comparison between the volume of data in visible and near infra-red wavelength in a MEIS 5 km x 5 km tile and that contained in a standard Landsat TM and SPOT HRV image. Fortunately, the massive reduction in the cost of computer hardware in recent years means that data storage problems are largely a thing of the past, and even quite a modest PC could now handle the 50 Mb tiles with ease.

A second, more difficult problem was created by the decision to georeference and mosaic the individual flightlines. There were good practical reasons for specifying this as part of the original contract with Innotech, and it was expected that this would facilitate the creation of accurate maps, but the reverse turned out to be the case. As Figure 5.6 shows, the effect of geocoding the flight lines was to create tiles which, in many cases, had large expanses of background. This not only wasted storage capacity (all the background pixels were set to 255), it created problems with some of the image processing operations which assumed the background pixels were valid data. More recent versions of industry-standard software have recognised this problem and it is now common to be able to confine all operations to a 'region-of-interest', but again, in the early stages of this research it was necessary to devise a 'work-around' using a series of boolean masks and this complicated the analysis process.

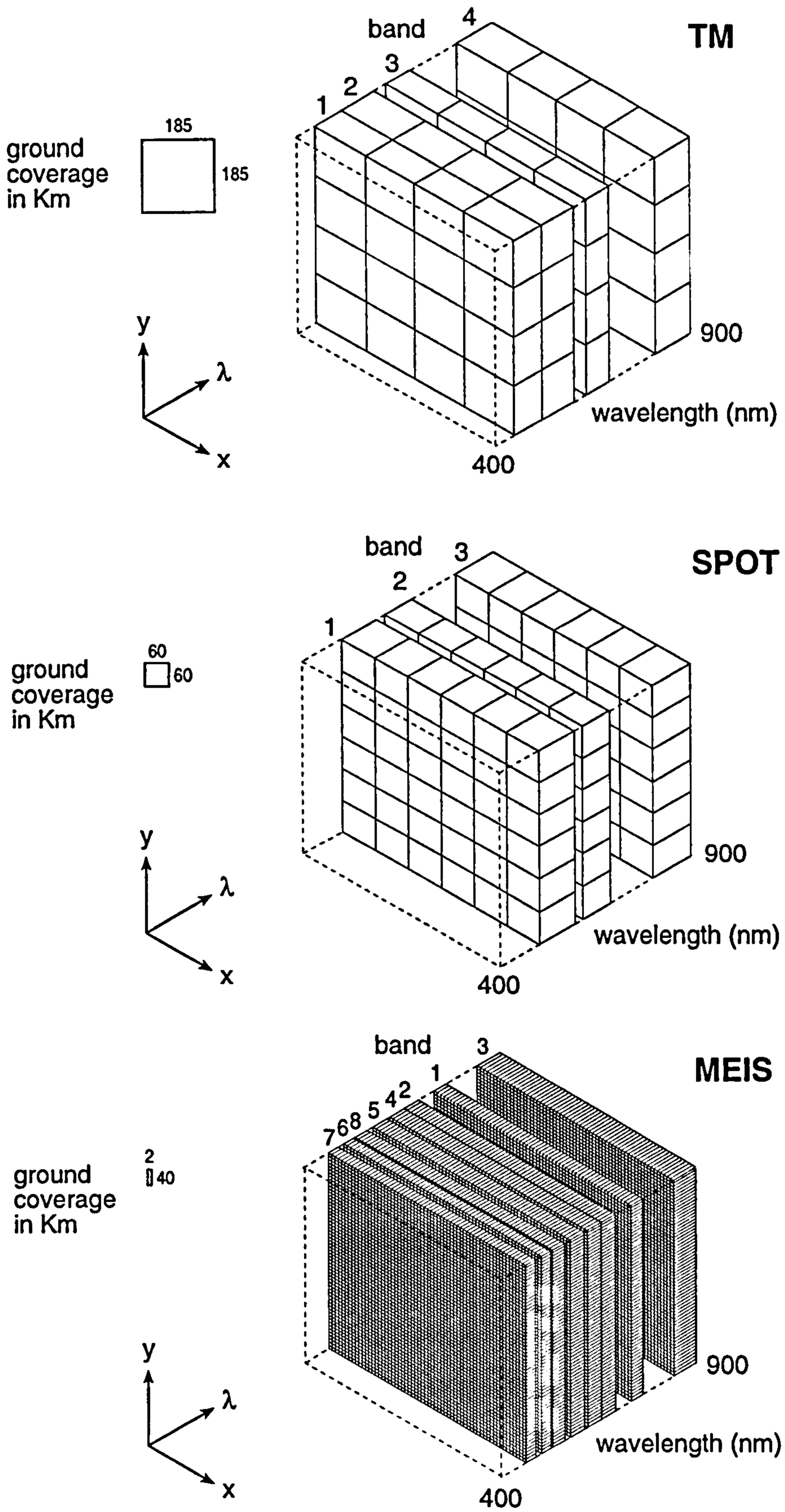


Figure 5.5 A visual comparison between the volume of data in visible and near infra-red wavelength in a MEIS 5km x 5km tile and a standard Landsat TM and SPOT HRV image.

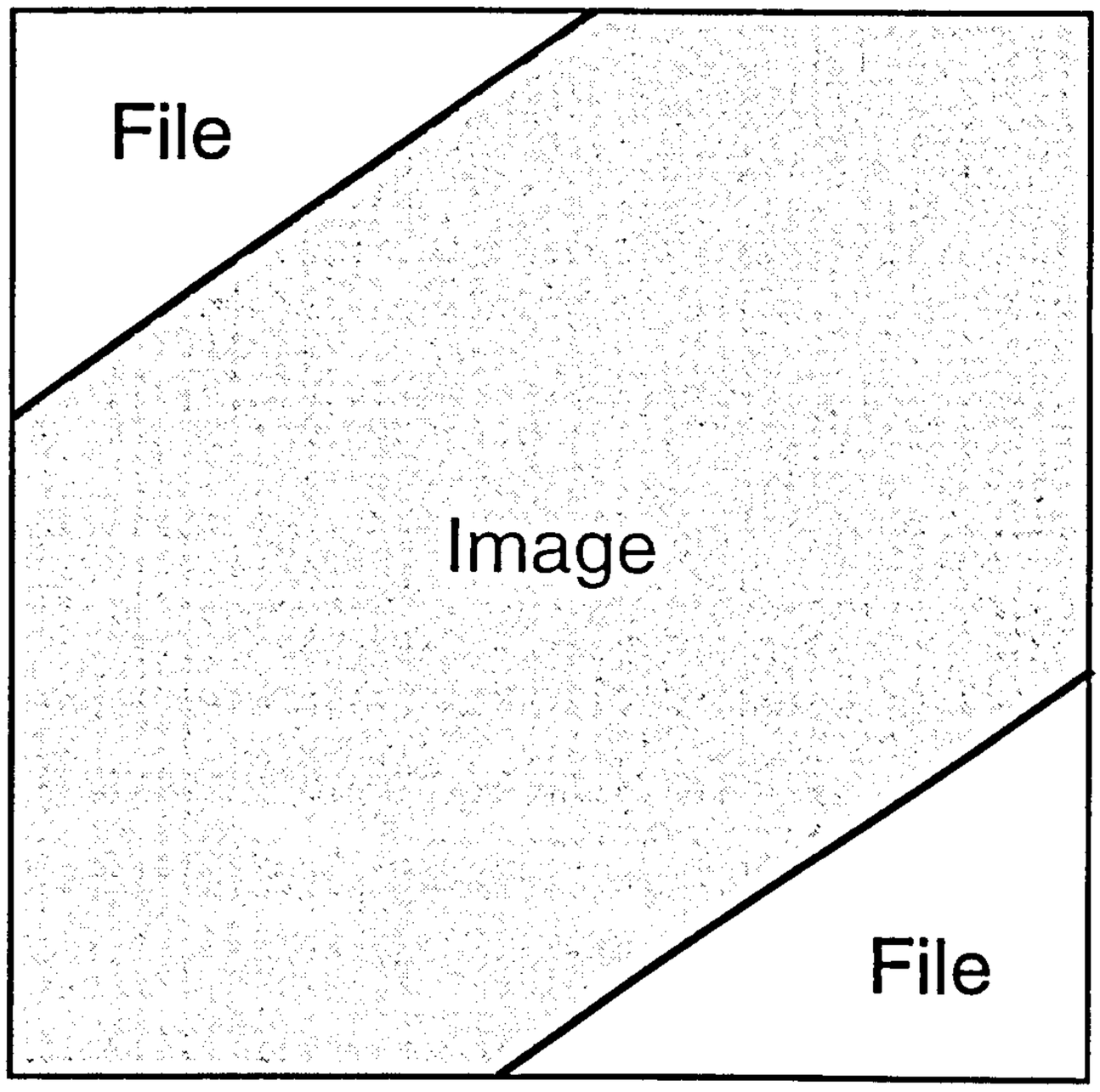


Figure 5.6 Mosaic tile illustrating the image data and the pixels outside the acquisition sector which are set to 255.

The mosaicking process also created a further serious problem which proved to be insurmountable in the time available. For logistical reasons, it was often necessary for there to be a delay between the collection of data from adjacent flight lines. The effect of this upon the data was expected to be minimal, but, as it turned out, changes in solar geometry, allied with the bi-directional reflectance effect from many of the ground targets, meant that there were noticeable differences in brightness between adjacent flightlines (see Figure 5.7). It would have been possible to correct for this by a process of radiometric balancing prior to geocoding, but this was not done, and once the data were warped to fit the map base it would have been very time-consuming to reverse the process and make the necessary changes. The residual striping varied in severity; some tiles were little affected, others were almost unusable in any computer-based analysis. The full scale of this problem only became apparent as the research progressed because the process of displaying and processing tiles was so laborious, and many of those viewed in the early stages were hardly affected. The striping was also made much more evident by the more advanced techniques of image processing as will be shown later.

The final problem encountered was equally serious, and could not be corrected because it appeared to have arisen either in the sensor itself or in the primary data processing. It is shown in Figure 5.8 as a noticeable blurring towards the upper right section of the image and repeated groups of pixels - a sort of double-vision effect. This was not present on all the tiles and its cause remains a mystery. However, where it does occur it is serious enough to preclude most forms of automated image classification.

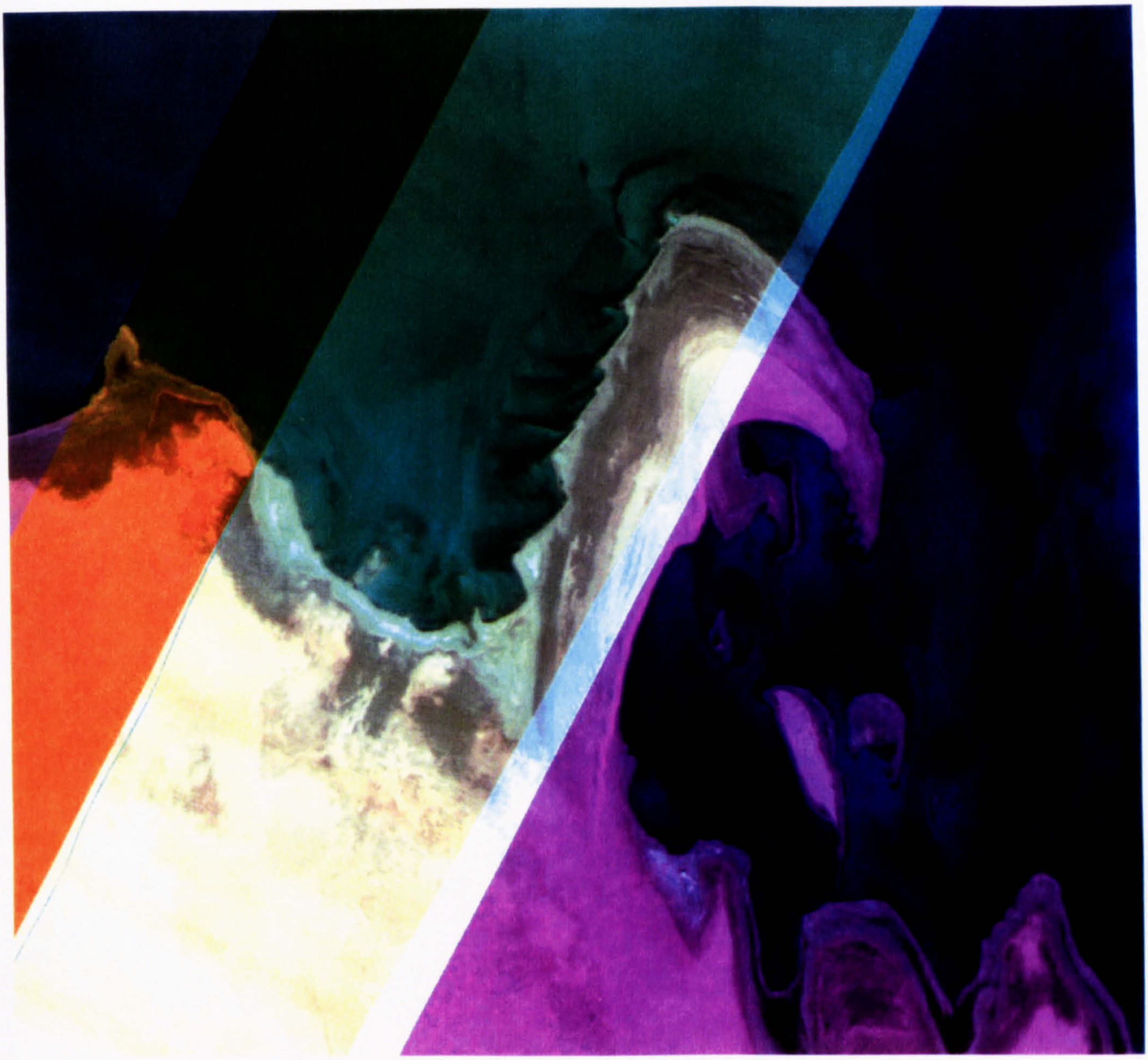


Figure 5.7 The problem of striping caused by the differences in brightness between adjacent flightlines.

Figure 5.8 The problem of blurring (double-vision) effect caused by the system.

Therefore, the MEIS data set which forms the backbone of the remote sensing component of this research was not without its problems, and this was always in the forefront of my mind when working with it. On the one hand, it can be said to be seriously flawed, and any analysis from it compromised, on the other hand, it represents the best data set available for the purpose, and it is without doubt an immensely valuable resource for use in the management of the coastal zone of Qatar. The aim of the following sections of this Chapter is to reconcile these two points of view; to use the MEIS data in the most appropriate way, and to learn from what must be one of the most complete airborne multispectral surveys of any country in the world.

5.5 ANALYSIS OF THE AIRBORNE MEIS DATA SET

> "The coastal environment and its resources are under strong pressure from population growth, industrialisation and tourism throughout the developing world. Integrated management is widely recognised as the basis for sustainable use. The first step toward this often involves an evaluation and mapping of the resources using remote sensing techniques ranging from aerial photography to satellite imagery. Such an approach can be an effective means for a developing nation to improve its management of coastal resources."
>
> (Clark *et al.*, 1996)

Remotely sensed data has great potential for dealing with the complex environmental problems in the coastal zone. In order to realise this potential it is necessary to interpret and extract useful information from the remotely sensed data. In the context of the present research, the most useful information comprises an Environmental Sensitivity Index (ESI) map for the coastal zone.

Remote sensing technology has been applied before in ESI mapping (Jensen *et al.*, 1990; Jensen *et al.*, 1992; Narumalani *et al.*, 1992) using spaceborne remotely sensed data. However, the use of high spatial resolution airborne data for ESI mapping has not been investigated before for such a large area and in so much detail (2m spatial resolution) and the area chosen for study, northern Qatar, has no ESI information for it, collected by any means. Therefore, three tasks are involved in the present analyses of the airborne MEIS data. First, management of the large volume of the digital data so it can be analysed most efficiently; second, extraction of the information needed for the coastal zone from the large volume of digital data; and, third, creation of the ESI map through integration of the remotely sensed data with other data in a GIS.

> "Image processing systems provide the ability to extract and analyze information from multi-date, multi-spectral raster format data at multiple resolutions. The information extracted from raster imagery can be based on the analysis of spatial and spectral frequencies as well as on the shape and distribution of image features. The information extraction process varies from highly interactive (e.g. an analysis by a photo interpreter) to highly automated (e.g. an unsupervised classification). The extracted information is generally presented in the form of a thematic map."
>
> (Aronoff and Parliament, 1987).

To assess a number of different ways of processing the MEIS digital data set, a mosaic covering the extreme north of the coastal zone of Qatar was used (Figures 5.11). This part of the coastal zone of Qatar is considered to be a very sensitive zone and extremely vulnerable to any oil pollution that might occur in the Gulf. This mosaic tile covered an area of 10 km by 10 km and was 5000 pixels by 5000 lines by eight MEIS spectral bands. The following section discusses the various image processing methods that were applied to the data.

Three types of analyses have been applied in order to find the best technique that can suit this type of data and the environmental and physical conditions in the coastal zone of Qatar: 1) automated image classification, 2) pixel unmixing, and 3) visual interpretation of enhanced colour composite images (Figure 5.9). An important first stage in each of these analyses involved procedures to reduce the volume of the data set in such a way that important information was retained but redundant information excluded.

5.5.1 Image classification techniques

Since the aim of using remote sensing is to produce a land cover map of the coastal zone habitats suitable for exporting to a GIS system. Image classification technique was first applied to the MEIS digital data. The objective of classification process is to automatically assign all pixels (picture elements) of an image into classes of land cover types or themes.

Usually, multispectral bands of image data are used, and each pixel in these spectral bands consists of digital values. Pixels of features with different spectral patterns will have different digital values. By comparing all pixels to one another or to pixels with known identity, it is possible to create an output image with a finite number of individual classes that are similar to the informational classes on an image or a map which are of interest to users of remotely sensed data (Campbell, 1987). By assigning colours or symbols to these classes, a map of uniform parcels can be produced. Pixels in an individual class are more similar to each other spectrally than to pixels in other classes. Spectral pattern recognition is the automated process or procedure that categorises the pixels, pixel-by-pixel, based on their digital information into different land cover classes (Lillesand and Kiefer, 1987).

Two types of spectral pattern recognition algorithms are used for digital image classification. In the first type, an automatic clustering algorithm is used to classify the pixels in the data file into classes based on their natural groupings. The analyst defines the number of spectral classes to be used for grouping the digital data. Then the clustering algorithm searches for these distinct spectral classes, and uses them to classify the whole image. This technique of classification is known as unsupervised classification.

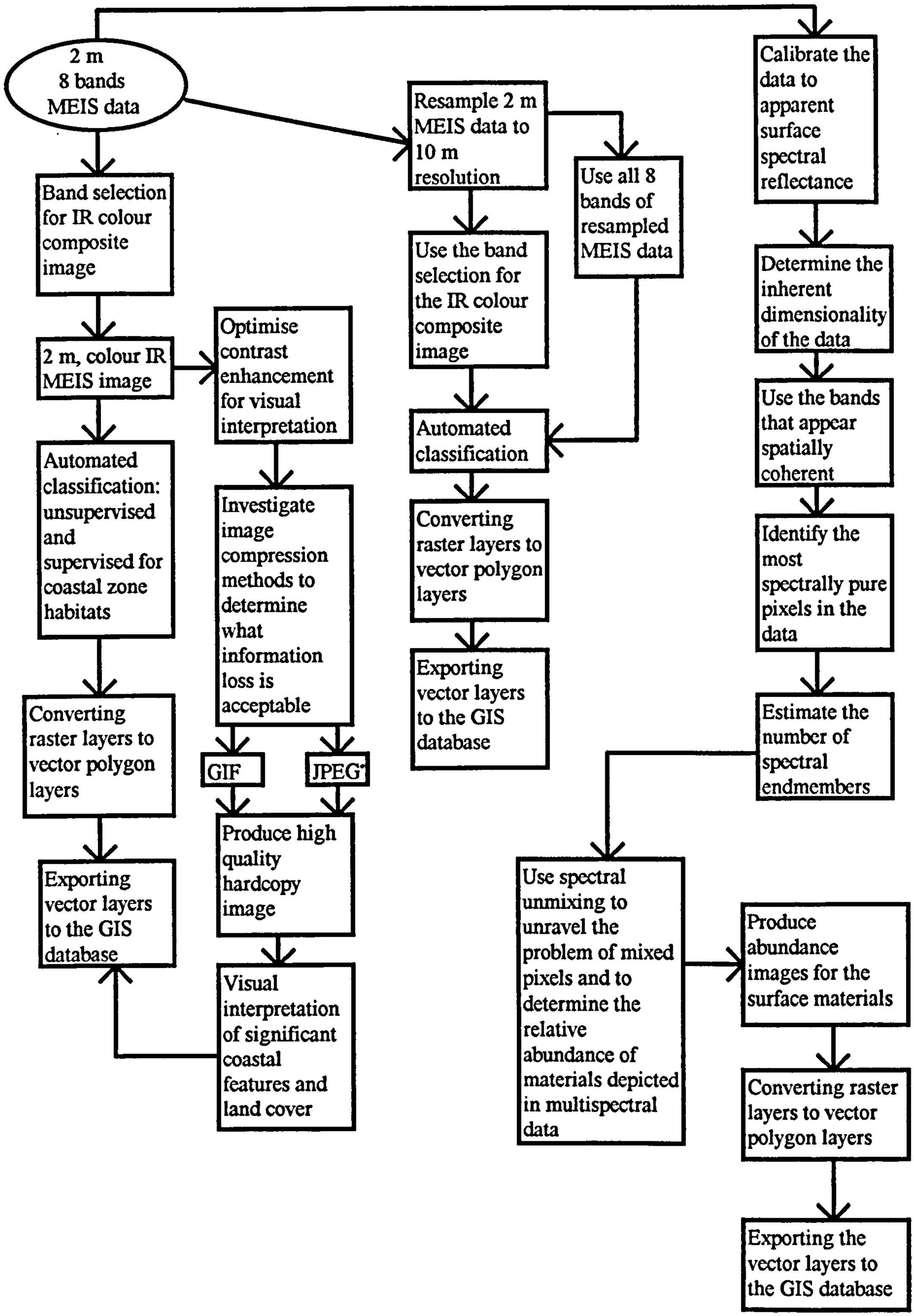


Figure 5.9 General flow chart showing the various processing techniques applied to the MEIS data to produce a land cover map of the coastal habitats in northern Qatar.

The second type of spectral pattern recognition algorithm is called supervised classification. In this technique the analyst has to build up training areas by taking sample sites of known cover types. By giving names to each training area and specifying the classification algorithm to be used, the computer then uses these training areas of known cover types as interpretation keys to classify the whole digital image. In both types, the output is a useful classified map that can be exported easily to a GIS system for more manipulations. It is difficult to apply the classification techniques on the eight MEIS bands all at one time because image file so large which will requires very long time for processing. Therefore band selection should be made first. Figure 5.10 shows the flow chart of the classification methods applied to the 2 m MEIS mosaic data.

5.5.2 Band selection of the airborne MEIS data

Three of the MEIS bands were selected for automated classification, based on visual inspection of a large number of possible image triplets, constrained by knowledge of the spectral properties of the targets of interest (Lillesand and Kiefer, 1987 ; Narumalani *et al.*, 1993). The bands finally chosen were the green wavelengths (533-564 nm MEIS Band 8), red wavelengths (655-695 nm MEIS Band 2) and near infrared wavelengths (846-901 nm MEIS Band 3). The false colour composite image of these three bands was found to be the best band combination to identify and map the vegetated habitats in the coastal zone of northern Qatar. The image shows a great deal of information especially in the intertidal zone, an area that is very important ecologically. A PC-ERDAS system (version 7.5) was used to subset all those three bands from the original MEIS file (8 bands). A file with only three bands was created (Red, Green, Blue 3, 2, 8) this is also was done to reduce the size of the original data file to a smaller size (52, 931, 592 bytes) that can be handled by both the space in the computer and the time of the image processing. PC-ERDAS software was used in addition to classify the data in order to identify and map any vegetated habitats in the coastal zone of Qatar that would be severely damaged by oil spills. Two types of vegetated habitats were classified in the intertidal zone for the first time in Qatar by using this MEIS data. These habitats were seagrass beds and *Arthrocnemum glaucum* (Halophytes).

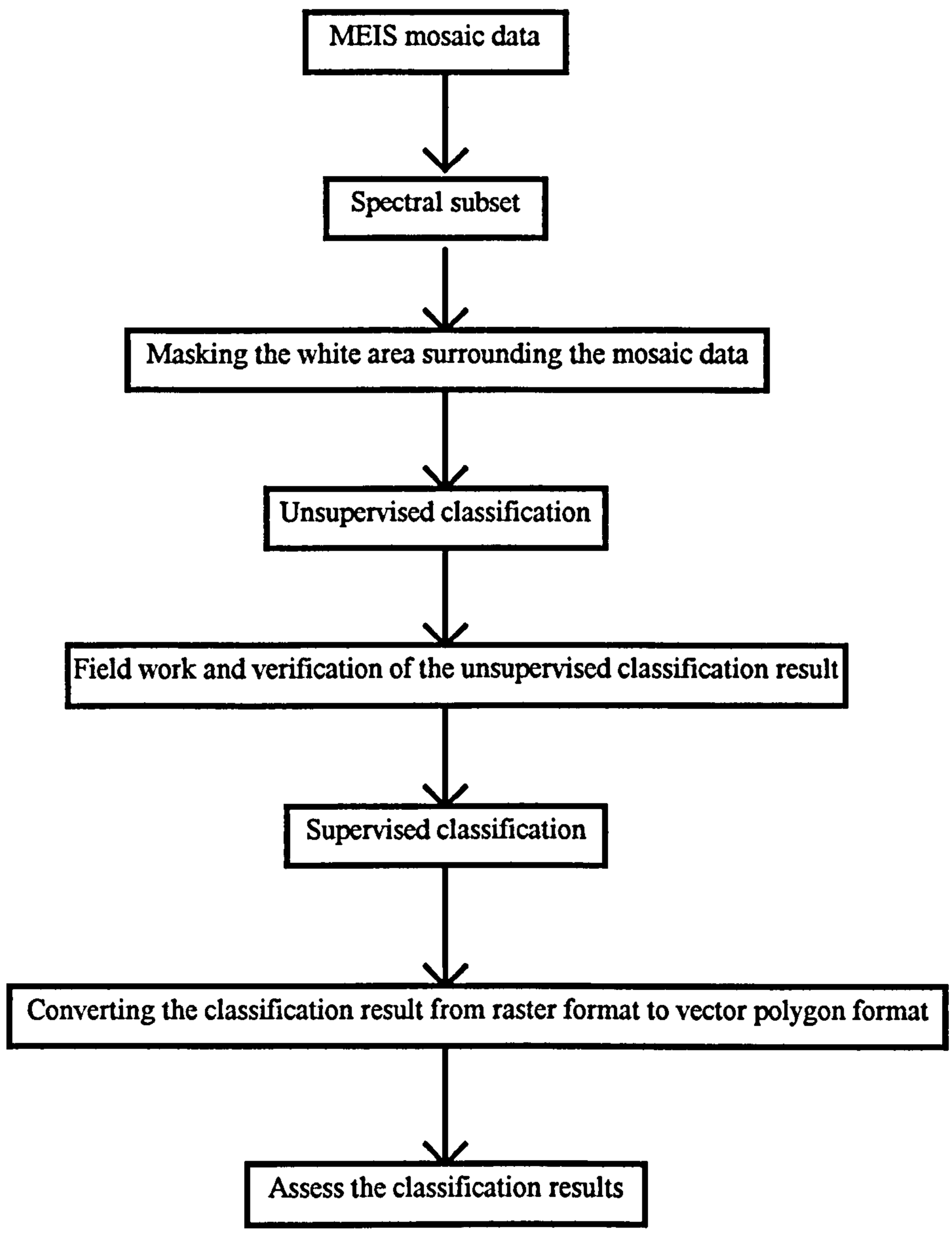


Figure 5.10 The flow chart of the classification methods applied to the 2m MEIS mosaic data.

It is worth mentioning here that the three bands selected by visual inspection differed slightly from those chosen by the CCRS using a statistically based approach (the method of Chavez *et al.*, 1982). This approach identified the following triplets as containing most variation (Prevost and Pouliot, 1991b):

Mangrove area	Full scene
1) bands 1 3 6	1) bands 1 2 3
2) bands 1 5 6	2) bands 1 2 8
3) bands 1 6 7	3) bands 1 2 6

The 'best' band combinations identified by the CCRS for both the mangrove area and the full scene included both near IR bands which seems counter-intuitive and the triplet selected by visual inspection was clearly superior for the specific task in hand.

Figure 5.11 shows the MEIS mosaic covering the extreme north of Qatar after masking out the pixels outside the acquisition sector. As mentioned earlier that MEIS bands 3, 2, and 8 were used as Red, Green, and Blue to produced this mosaic. These bands found to be very useful for display and analysis of MEIS data. The red tones on this colour infrared image represents infrared energy reflected from the living vegetation in the coastal zone area.

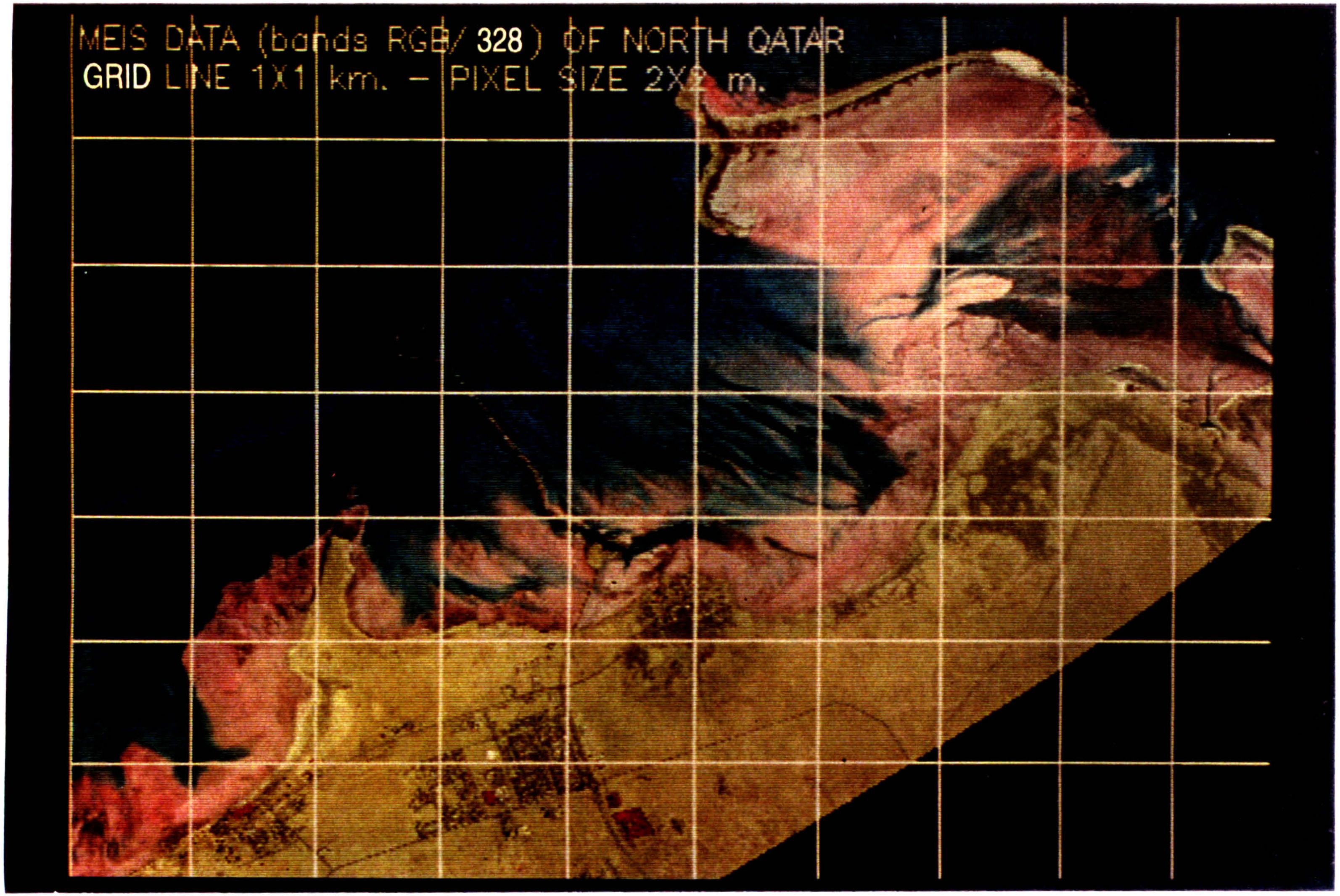


Figure 5.11 MEIS mosaic (10 km x 10 km) covering the extreme north of the coastal zone of Qatar.

5.5.3 Unsupervised classification technique applied to the airborne MEIS data

An unsupervised clustering algorithm was used first to statistically classify the MEIS image. A minimum distance algorithm was used to assign pixels to classes but the result was rather noisy, showing a "salt and pepper" effect. Therefore field work was necessary to obtain more information about the different regions visible in the MEIS colour infrared composite image and to verify if possible the result of the unsupervised classification. Familiarity with the different regions in the image and the ground is very important for the interpreter and the information extraction process.

A hardcopy of the classified image plus the colour composite MEIS image were used in the field work that took place after the unsupervised classification. Since the MEIS image was geometrically corrected to the Transverse Mercator (the same projection of topographic maps in Qatar), it was possible by using the ERDAS system to overlay a grid layer of 1 km^2 apart onto the colour composite image for easy identification of locations in the images and the ground (Figure 5.11).

In addition transect locations were selected from the hardcopy of the MEIS colour composite image to cover and cross areas in the land and intertidal zone which information about habitats could be obtained. A GPS system in conjunction with the topographic maps of northern Qatar (scale 1 : 50, 000) was used also in the field work. A better understanding about the different colours in the MEIS image and the types of habitat on the ground was obtained. The MEIS image was extremely useful for mapping seagrass beds in the shallow water of the intertidal zone (0.75 m deep) and *Arthrocnemum glaucum* along Ras Rakan island (extreme north of Qatar). No information was available before about the location and distribution of these sensitive vegetated habitats in that area of Qatar.

5.5.4 Supervised classification technique applied to the airborne MEIS data

By using the information obtained from the field work, a supervised classification technique was performed using again ERDAS system to classify the MEIS colour composite image. A signatures file was built for the various cover types (identified in the image from the field work) by drawing polygons of uniform areas inside each cover type. These polygons were saved in the signatures file to be used later in the classification as training sets or samples representing the various cover types in the image. A maximum likelihood classification algorithm was then used to classify and assign each pixel in the image to the training set or polygon area (in the signatures file) of which it had the highest probability of being a member. The result of the classified map was then overlaid onto the original image to assess the quality of the classification information and a satisfactory result was obtained, however, some "salt and pepper" effects still remained.

Figure 5.12 shows the final classified map resulted from the supervised classification technique. Notice that the *Arthrocnemum glaucum* plant was classified as salt marsh, since this plant most commonly grows in the saline flats (sabkhah) of Qatar. In addition, the sensitive salt marsh, seagrass and intertidal zone will receive the highest ranking in the Environmental Sensitivity Index (ESI) because of long oil persistence and high biological value.

The salt marsh area is a notable breeding and resting area for a large number of two types of water birds (*Socotra cormorant and Kentish plover*). While the seagrass beds is a feeding area for the most popular and expensive fish (*Siganus canaliculatus*) in Qatar and the Gulf region. The intertidal zone is a feeding area for water birds when it is in low tide, and for fish when it is in high tide. Both the intertidal zone and the salt marsh act as international airports for the migrating birds. Salt marsh, seagrass and intertidal areas, therefore, will have the high priority for protection.

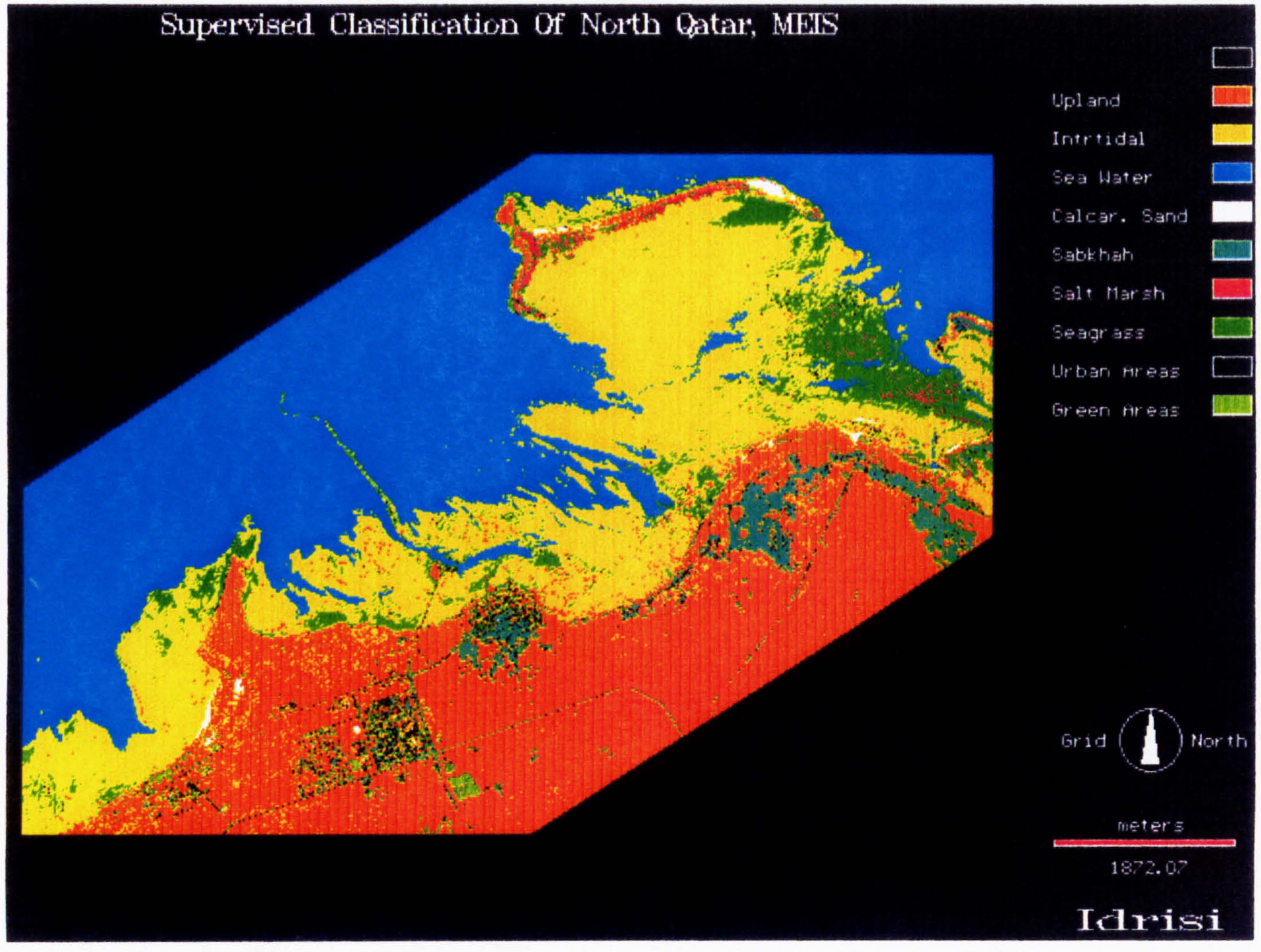


Figure 5.12 A supervised classification map of the extreme north of the coastal zone of Qatar.

Visual inspection of the classified image and comparison with the ground data collected during fieldwork in Qatar showed it, for the most part, to be highly accurate and a procedure to formally test the accuracy of the classification was initiated. However, as this progressed, it became clear that the problems with the MEIS sensor described in Section 5.4 meant that a normal assessment of classification accuracy based on a sample of pixels would not be very meaningful. For example, parts of the image were replicated, and while these were classified correctly according to the pixel DN values, a human interpreter looking at the scene could easily see that they were in error. It became clear that conventional automated classification of the MEIS data was probably not the most efficient way to handle this particular data set.

Furthermore, doubts began to arise as to whether 2 metre resolution data were actually needed for the task. The very high spatial resolution led to a large number of small polygons in the classified image, some of these were possibly sensor noise but the vast majority were real and reflected the presence of very small objects on the ground - a small bush here or there, or a patch of slightly damper ground in a sabkhah. Internal variation such as this is known as 'scene noise' and can be removed by applying a spatial filter (e.g. median or modal filter). However, in some parts of the scene (e.g. mangrove and intertidal creeks) this level of detail is required to map the ground features and therefore any spatial filtering must be applied with great care.

5.5.5 Converting the raster layer of the airborne MEIS data to vector polygon layer

The classified map was imported into the IDRISI GIS package in order to convert it from a raster layer to a vector polygon layer so it could be exported to the SPANS GIS system where the data base of the northern Qatar coastal zone was being constructed. This route was chosen as it mirrors the capabilities available in Qatar. Unfortunately, the large number of polygons present in the classified image exceeded the capabilities of IDRISI and it was not possible to use this method of raster to vector conversion. The vector file was huge: over 17.5 Mb. To overcome this problem a method of on-screen digitizing was used. The classified image was displayed on-screen in IDRISI and the mouse used to create accurate polygons for each of the informational classes in turn. The digitized polygons for the two important classes of salt marsh and sea grass are shown in Figure 5.13.

5.5.6 Assessment of the automated classification route applied to the 2 metre data

These initial results showed both the potential of this very high spatial resolution data set and its limitations when subjected to automated analysis. The initial false colour composite produced (Figure 11) showed a wealth of useful information on the coastal environment, but extracting this and exporting the appropriate vector information to the GIS was a very difficult task, partly due to the inherent problems of the MEIS sensor, but also because of the spatial complexity of the coastal environment. It was also a matter of concern that not all eight bands of the MEIS data had been used in the classification due to the limited disk space available, and this meant that its full potential may not have been tested. In order to answer this question, and also settle for certain whether such high spatial resolution data were really necessary for the task, a second image processing route was established using a spatially degraded version of the original MEIS data.

Figure 5.13 Vector layers of the salt marsh and seagrass produced from the supervised classification map covering the extreme north of the coastal zone of Qatar.

5.5.7 Analysis of the spatially degraded airborne MEIS data

The original MEIS image at 2 m pixel resolution was resampled to 10 m pixel resolution (Figure 5.14). Nearest neighbour resampling and a 5 x 5 low pass filter was used. The size of the resampled MEIS image data file was then reduced to approximately 8 Mb. The same classification techniques were then applied to the resampled image (10 m spatial resolution). First, the classification was performed only on the same three bands of data as were used for the full-resolution analysis. These bands are band 8 (533-564 nm), band 2 (655-695 nm), and band 3 (846 -901 nm) of MEIS data.

A supervised classification technique using the maximum likelihood algorithm was performed using ERDAS IMAGINE software. A signatures file was first built for the various cover types by drawing polygons of uniform areas inside each cover type. These polygon areas were used by the algorithm as training sets or samples to classify the whole image. Figure 5.15 shows the output result from the classification.

The same training sets was used also to classify the 10 m spatial resolution image but this time using all 8 bands of MEIS data rather than only three bands of data. The result is shown in Figure 5.16.

5.5.8 Assessment of the automated classification route applied to the spatially degraded MEIS data

Visual inspection of the results from both the 3-band and the 8-band classifications showed them to be greatly inferior to that produced from the 2 metre data set. The high degree of pixel mixing which inevitably occurred in the spatially complex coastal zone led to classification errors and excessive generalisation of the informational classes. Furthermore, variations in illumination intensity between adjacent flightlines became more of a problem (this is very clear in Figure 5.16). There was no evidence that including all eight MEIS bands produced a better result than just using the three bands used previously.

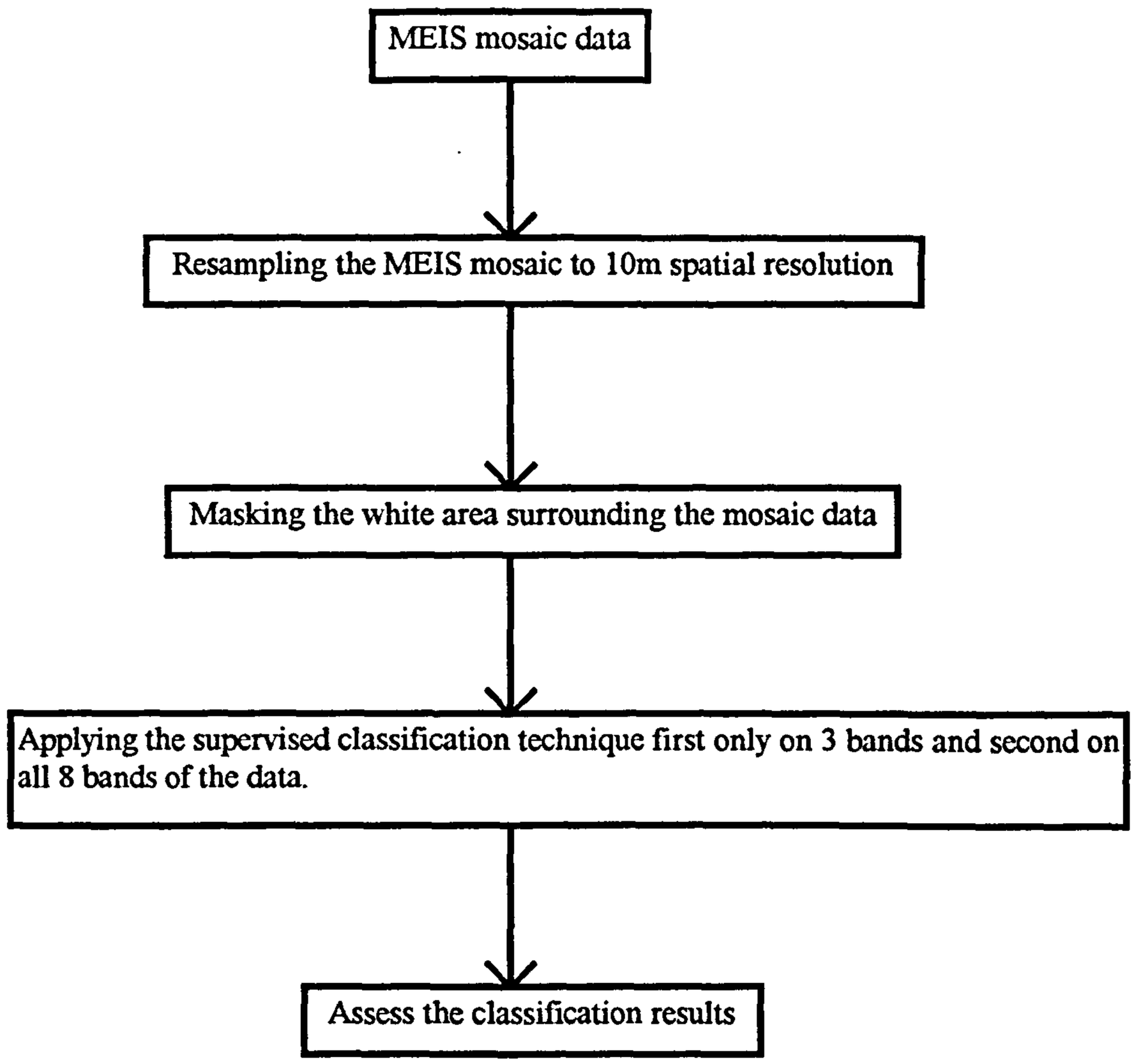


Figure 5.14 The flow chart of the resampling and classification techniques applied to the MEIS mosaic data.

Figure 5.15 Classification output from using three bands (RGB/328) of the resampled MEIS mosaic image.

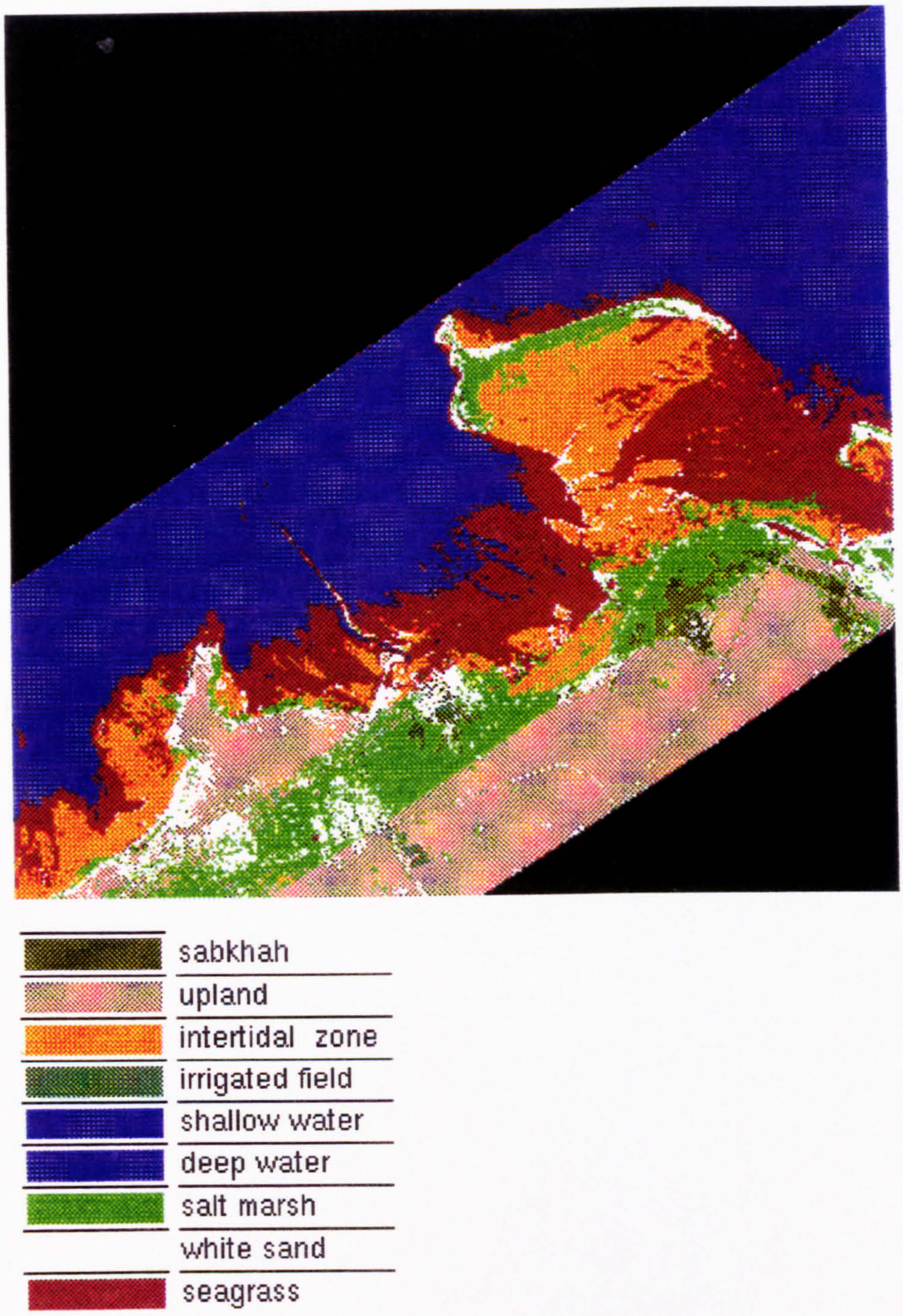


Figure 5.16 Classification output from using the eight bands of the resampled MEIS image.

The conclusion of this analysis of automated classification techniques applied to the MEIS data set for coastal Qatar was that it was important to retain all the spatial detail present in the original data set, but it was not necessary to keep all eight spectral bands. It is also clear that lessons can be learnt for the commissioning of airborne data sets which may be subject to automated analyses. These are:

1. Ensure that the sensor and associated processing chain is free from internal defects such as caused the blurring and 'double-vision' in this data set;

2. Think carefully about the data storage implications of geocoded data if the flight line is not orientated towards grid north;

3. Beware of mosaicking airborne multispectral data unless the radiometry of adjacent flightlines is very similar.

5.5.9 Automated spectral pixel unmixing analysis applied to the MEIS data

The results of the automated classification methods applied to the MEIS data highlighted one of the major problems of this approach to classify a spatially complex area such as the coastal zone. Airborne and spaceborne remotely sensed data suffer from mixed pixels which complicate the direct interpretation of the spectral data (Boardman, 1993). This spectral mixing is the result of sampling a heterogeneous natural surface with a sensor of finite spatial resolution. The finite spatial resolution of the remote sensing sensors strictly limits the image quality by introducing linear spectral mixing. The degree of linear spectral mixing presented in the remotely sensed data set is a function of the spatial scales of surface heterogeneity and the size of the ground instantaneous field of view (GIFOV) of the sensor (Boardman, 1994). Which means that decreasing the size of the GIFOV for a heterogeneous scene increases the variance in the data and makes purer pixels more likely (Boardman, 1994). The analysis used for unravelling this linear spectral mixing problem is pixel unmixing.

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Pixel unmixing analysis was first used for remotely sensed data in the 1970's, however, the technique has been used more extensively since the development of remote sensing sensors with many spectral bands thus increasing the inherent dimensionality of the feature space which allows the selection of those bands known to relate directly to spectral features in the objects of interest. Linear spectral mixture analysis (pixel unmixing) depends on the identification of the number of endmembers, their pure spectra and their spatial abundance patterns (Boardman, 1994). Various methods of identifying endmembers have been explained in the literature, however, the method used in this study was developed by Boardman (1993) and uses the concept of affine and convex geometry for deriving the number of vertices of the n-dimensional convex hull which contains all the data points.

The objective of this section of the research is to use pixel unmixing analysis in order to improve on the previous analyses of MEIS data. In addition to providing a method to cope with spatial complexity, pixel unmixing begins by using powerful procedures to collapse high-dimension data spaces into much smaller dimension feature spaces and it was expected that this would provide a way to retain all eight of the MEIS bands in the analysis without losing spatial detail. The three main objectives of this analysis are, first, creation of a low-dimensional MEIS feature space (typically 2-D or 3D) from the original eight spectral dimensions (bands); second, identification of the number of spectral endmembers present in the scene and their pure spectral signatures, and third, the use of these pure spectral signatures to unmix the spatial degraded MEIS data to determine the relative abundances of materials depicted in the imagery. The analysis was first applied to the 2m resolution data set, primarily to investigate the first and second of these objectives, it was then applied to the spatially degraded data set in order to investigate whether pixel unmixing could provide a way to extract useful information from this coarser data set.

The unmixing analysis used the ENVI (Environment for Visualizing Images) software package which uses a pixel unmixing algorithm developed by Boardman *et al.* (1995) for identifying endmembers based on the convex geometry of the data. In the present study the ENVI software package was used to unmix the airborne MEIS data mosaic covering the extreme north of Qatar. Figure 5.17 and Table 5.2 show the flow chart of the major steps and methods used in the automated unmixing analysis using the ENVI software package.

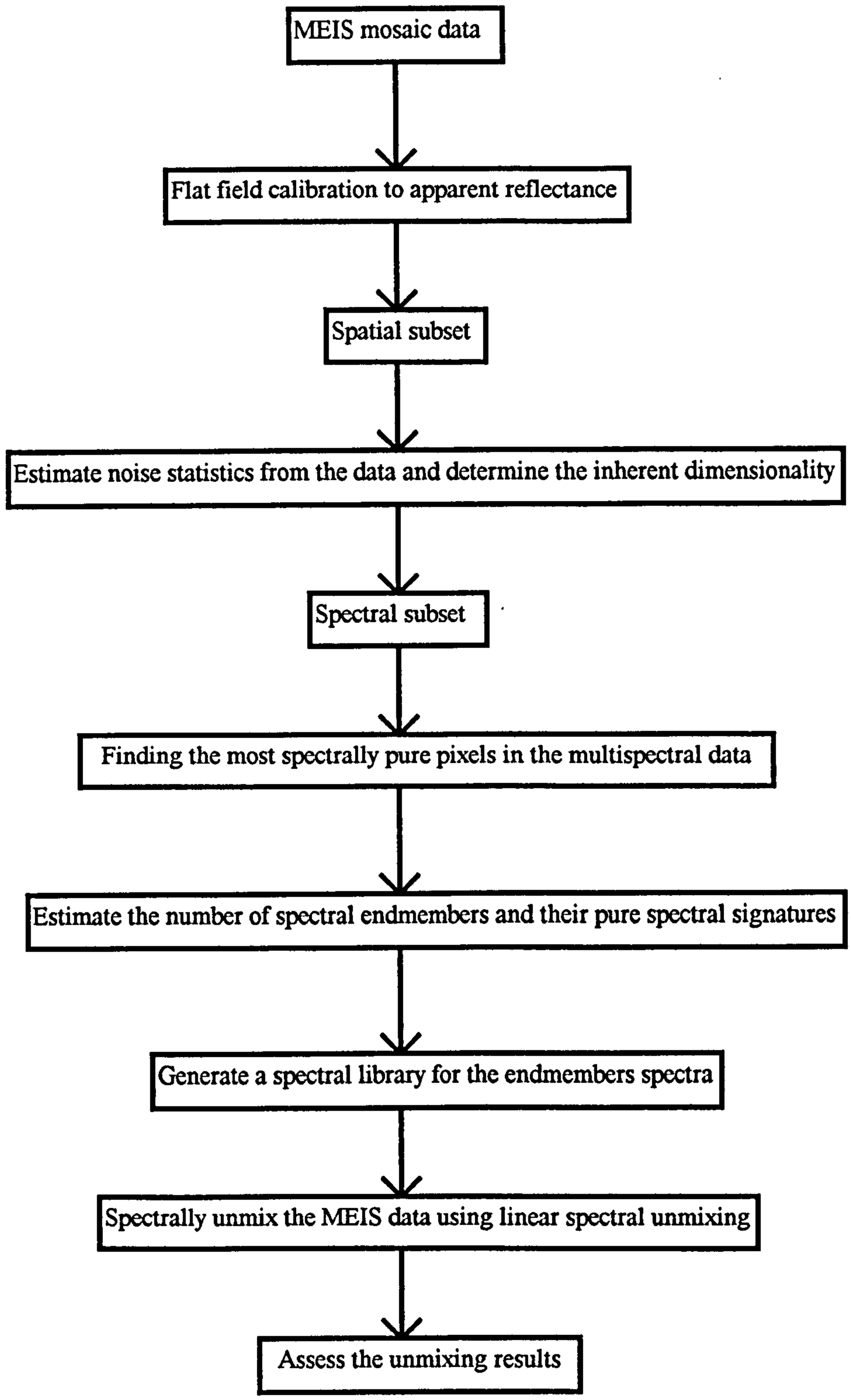


Figure 5.17 The flow chart of the major tasks used in the automated unmixing analysis.

Task	Method	Purpose
1. Calibrate image to reflectance.	Flat field calibration technique (Research Systems, Inc., 1995)	To normalise images from spectral radiance to apparent surface spectral reflectance.
2. Spatial subset.	Define regions of interest.	To reduce size of data matrix for subsequent processing.
3. The minimum noise fraction (MNF) transformation.	MNF transform (Research Systems, Inc., 1995)	To determine the inherent dimensionality of image data.
4. Spectral subset	Define regions of interest	To spectrally subset the MNF bands to only include those bands that appear spatially coherent.
5. Pixel purity index (PPI)	PPI technique (Research Systems, Inc., 1995)	To find the most spectrally pure pixels (extreme) in the MEIS data.
6. N-dimensional scatterplot.	The n-dimensional visualizer (Research Systems, Inc., 1995)	To distribute the pure pixels in n-space in order to be used to estimate the number of spectral endmembers.
7. Extract the pure spectral signatures of the endmembers.	Region of interest.	To generate a spectral library for the endmembers spectra and to be used as endmembers in ENVI classification routines or linear spectral unmixing.
8. Spectral unmixing.	Linear spectral unmixing (Research Systems, Inc., 1995)	To unravel the problem of mixed pixel and to determine the relative abundances of materials depicted in multispectral imagery based on the materials'

Table 5.2 Summary of the tasks undertaken in the automated unmixing analysis.

Firstly, MEIS data were reduced from spectral radiance to apparent surface spectral reflectance using the method of flat field calibration (Research Systems, Inc., 1995). The flat field calibration technique in ENVI was used to normalise images to an area of known flat reflectance. This was done first by identifying a region of interest in the image known from field survey to be uniform and lacking vegetation, and therefore likely to be spectrally flat. The technique then used the average spectrum from this region of interest as the reference spectrum and divided it into the spectrum at each pixel of the image (Research Systems, Inc., 1995). A spatial subset was generated from the calibrated output image to minimise the complexity of the analysis but at the same time maximise the range of endmember fractional combinations (Boardman, 1993). This spatial subset was then used for starting the linear unmixing analysis.

The second step involved was to determine the inherent dimensionality of the image data. This was accomplished using the minimum noise fraction (MNF) transformation (Green *et al.*, 1988). This is different from the more familiar Principal Components (PC) transformation in the way that PC analysis assumes any noise in the data is uncorrelated between bands and is of equal magnitude in all bands (Green *et al.*, 1988; Boardman, 1993). This in true in the case of Landsat TM data but airborne thematic mapper data do not behave in this way (Green *et al.*, 1988; Townshend, 1984). In other words, PC transformations do not always produce images that show steadily decreasing image quality with increasing component number, while MNF is a linear transformation that will always perform this function (Green *et al.*, 1988). In summary, the goal of the MNF transform is to identify the smallest-dimensions that adequately expresses the variability of the data, to separate noise, and to reduce the computational requirements for subsequent processing of the data (Boardman, 1993; Boardman, 1994; Research System, Inc., 1995).

Figure 5.18 shows the eigenvalues plot and Figure 5.19 shows the MNF bands (eigenimages), and both are the results from the MNF transformation. By comparing the eigenimages with the eigenvalues plot to determine which bands contain data and which bands contain predominantly noise (Research Systems, Inc., 1995), it is clear that the first three images appear spatially coherent (Figure 5.19: a, b, and c) while the rest of the images are very noisy, and the artifact of mosaicking is very obvious. In addition, the eigenvalues plot shows that only the first three MNF bands are above the break in slope of the MNF plot (Figure 5.18) which indicates that the inherent dimensionality of the data is three. Therefore, only the first three MNF bands are used for subsequent processing in the automated pixel unmixing.

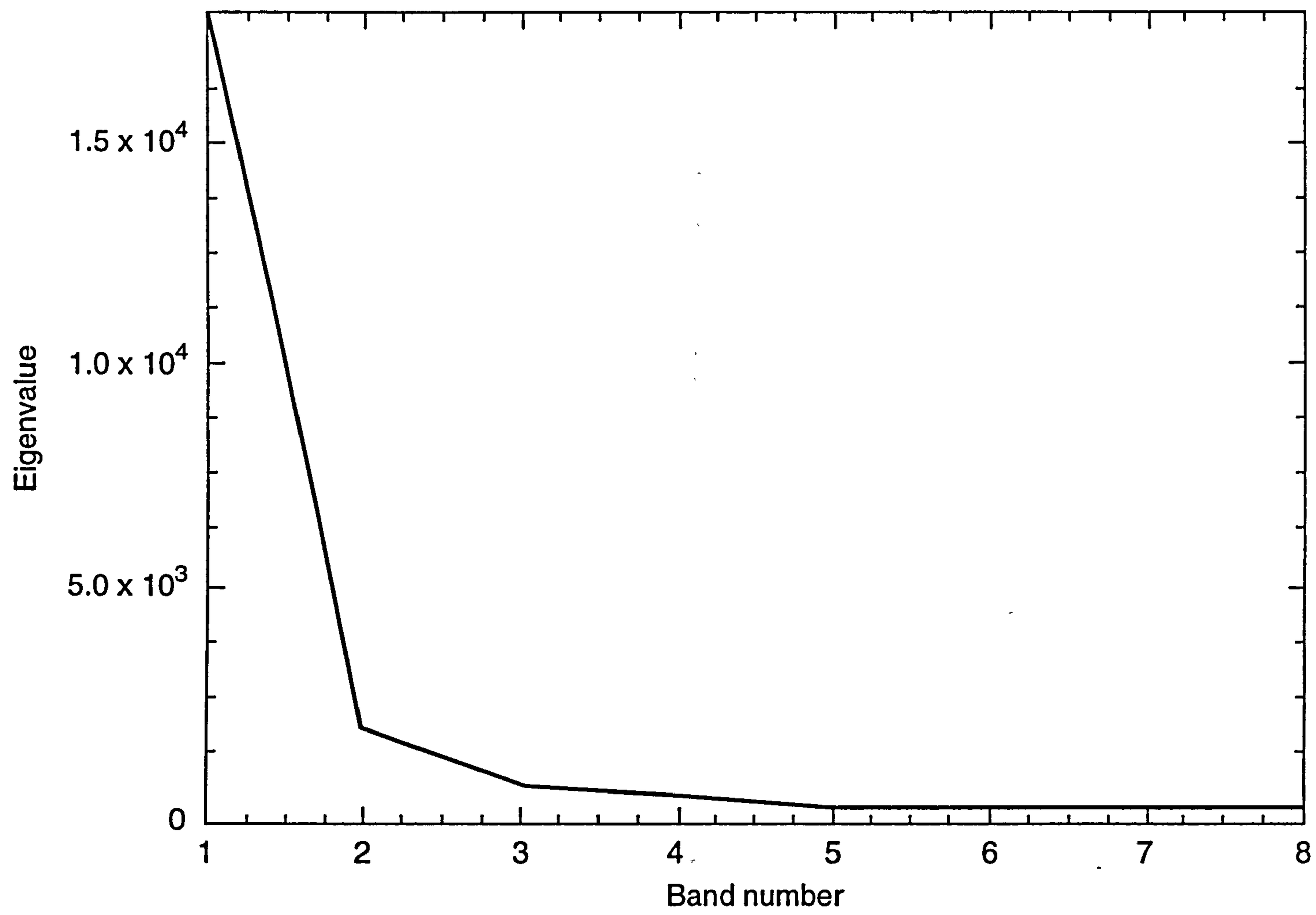
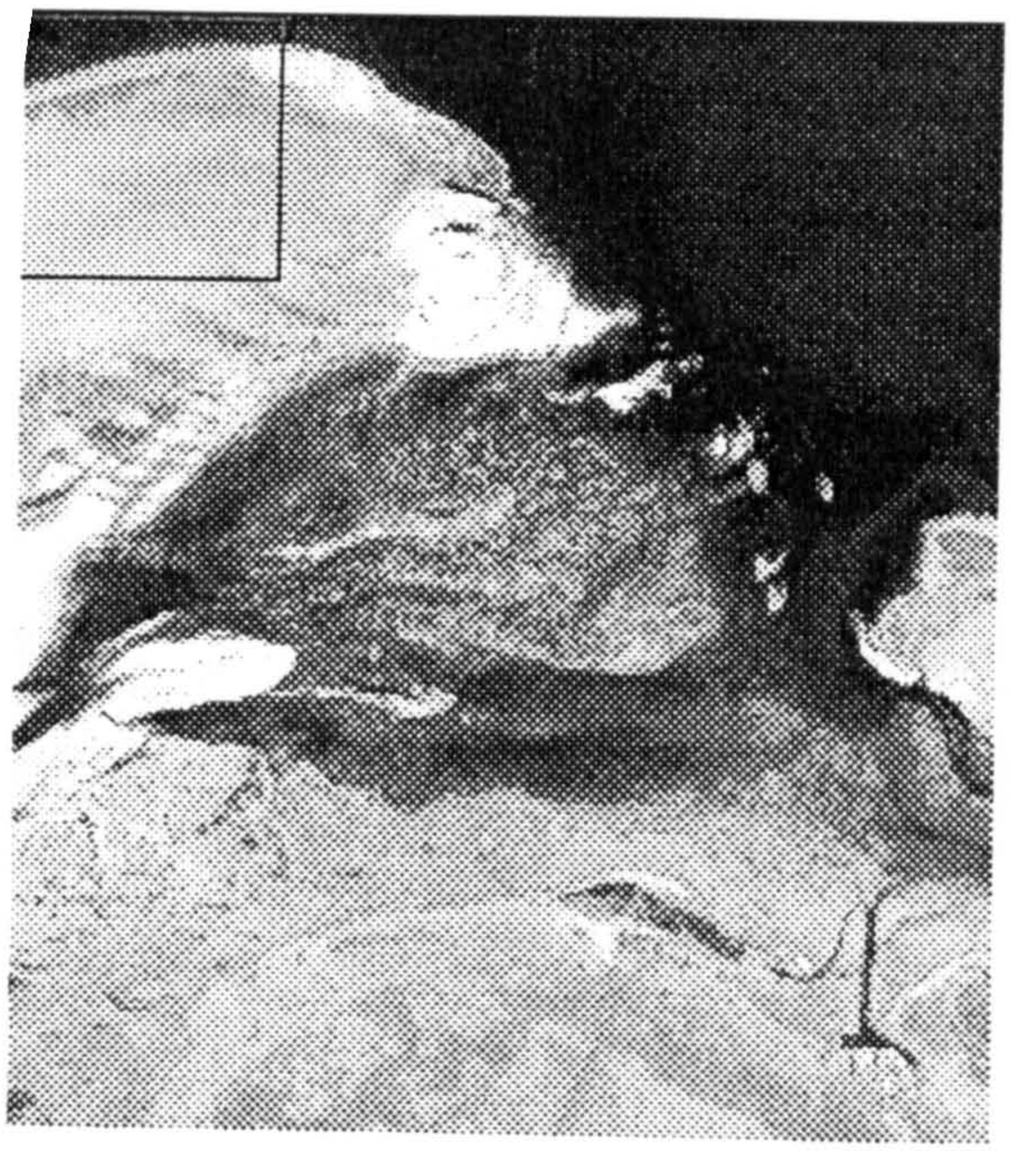
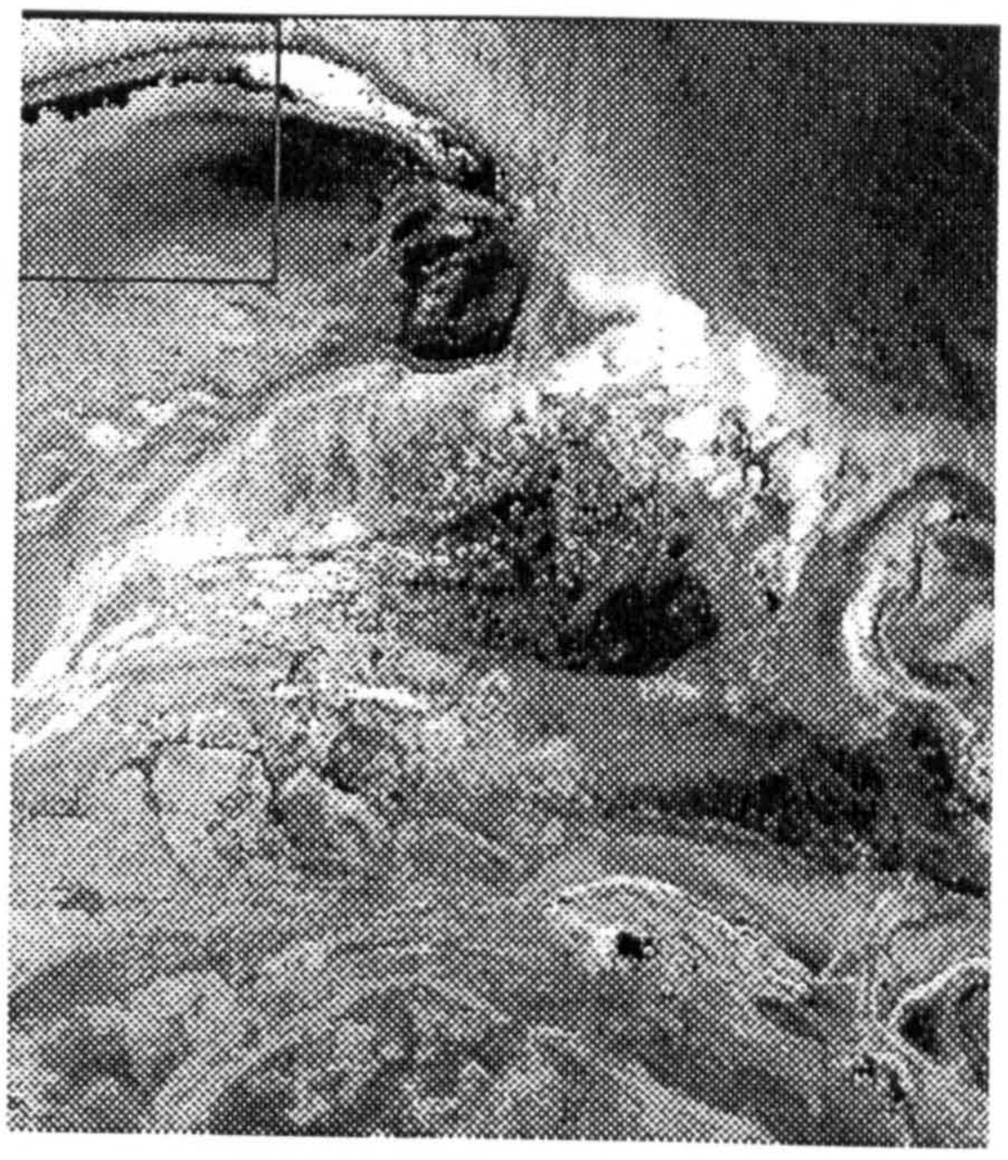


Figure 5.18 Eigenvalues from the MNF transform of 2m MEIS data.

a.



b.



c.

d.

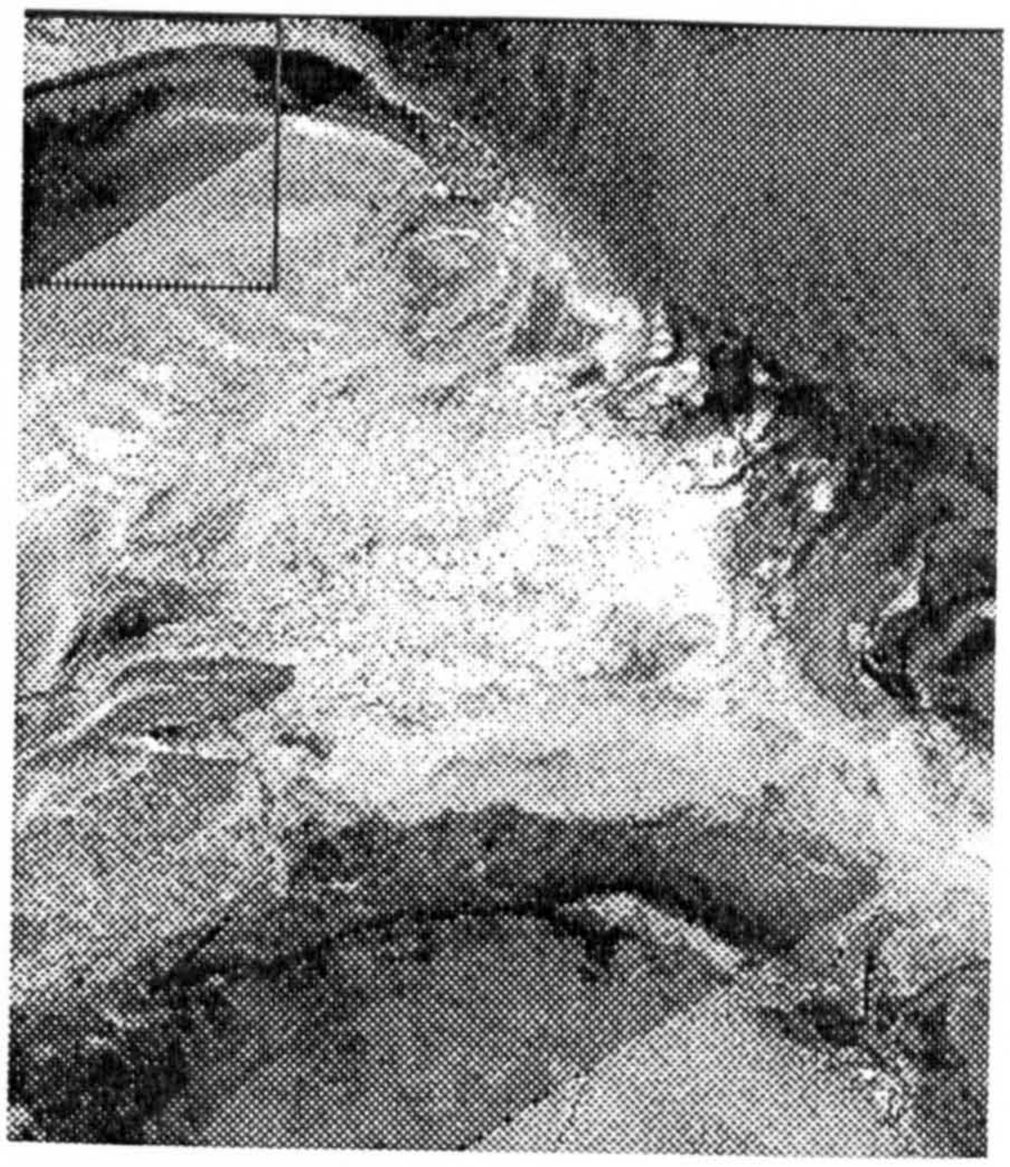
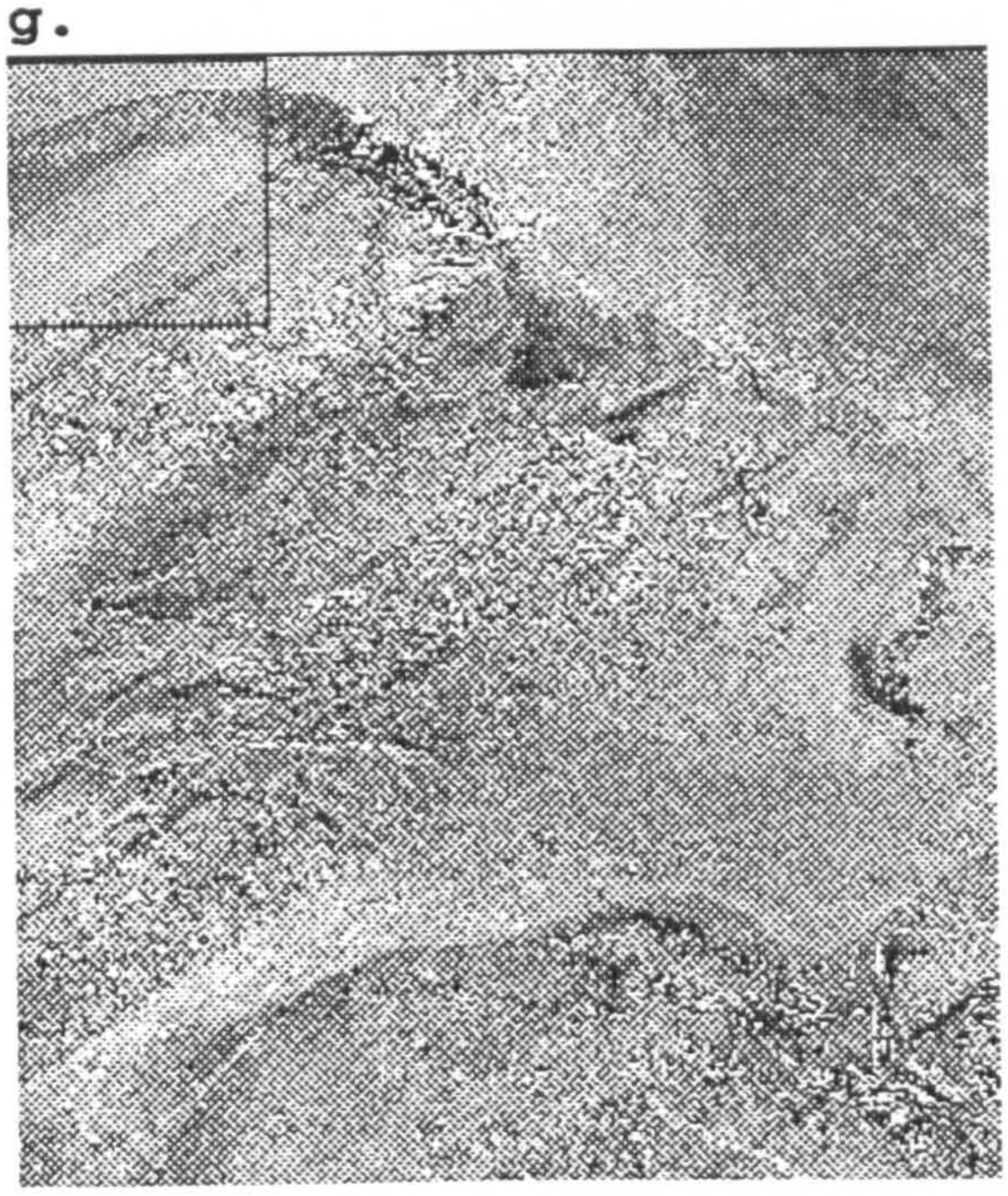


Figure 5.19 Eigenimages from the MNF transform of 2m MEIS data.

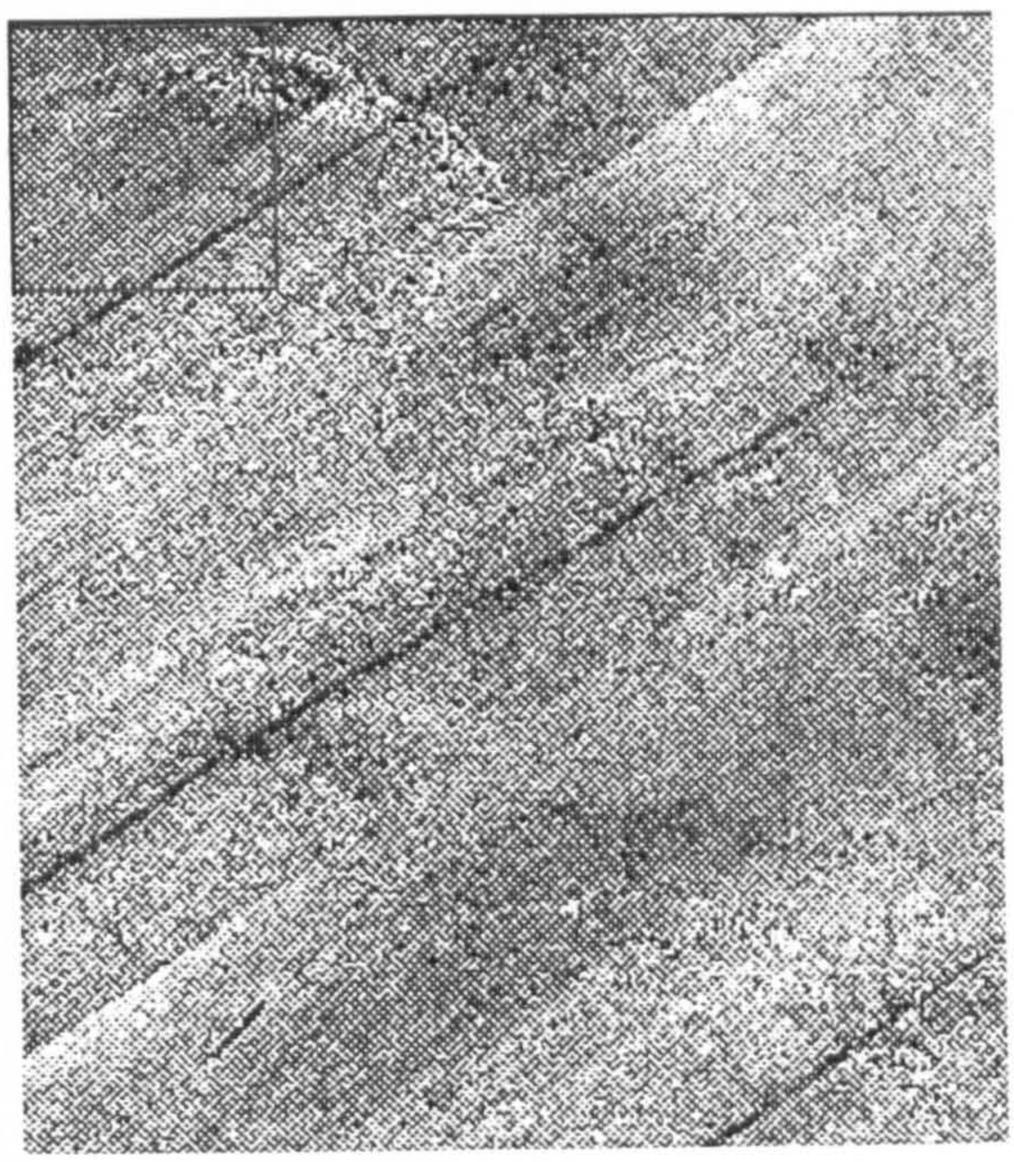
e.

f.

g.



h.



These three MNF bands were then used as an input to the "pixel purity index" (PPI) technique in ENVI which helps in finding the most spectrally pure (extreme) pixels in the image that correspond to mixing endmembers (Research Systems, Inc., 1995). Each pixel in the image is allocated a score based on how many times the pixel was found as pure pixel in repeated projections of the n-dimensional scatterplots onto a random unit vector. In addition, the resulting score was presented as a PPI image where the digital number of each pixel corresponds to the number of times that pixel was chosen as pure, which at the same time helps identifying endmembers (Research Systems, Inc., 1995).

Two small spatial subsets (covering almost all types of the surface material) were generated from the three MNF bands to run the PPI analysis. The reason this was done was to reduce the computational demands of the analysis but at the same time maximize the range of endmember fractional combinations (Boardman, 1993). The output results were then visualised as a scatterplot (Figure 5.20) using the n-dimensional visualizer in ENVI, where n is the number of bands (in this case, the three MNF bands).

The scatterplot shows the distribution of all points in the data that have been chosen at least once as being close to a vertex of the convex hull. Moreover, the distribution of these points in n-space helps in estimating the number of spectral endmembers and their pure spectral which are needed at the end to unmix the original MEIS data. This was done by selecting the three MNF bands to produce a 3-D sactterplot which could then be studied by rotating it in a 3-D axes to see the distribution shape of the data points defining the number of classes (endmembers).

The distribution of these data points defined a shape that is difficult to describe but which had several groups of points in the corners and along the edges of the shape with two or three points in the middle. By continuing the rotation process of the data points in the 3-D axes it was possible to isolate each class in turn from the main body of the shape and apply a colour coding scheme to the pixels in the feature space, which was then transferred to the same pixels in the image space.

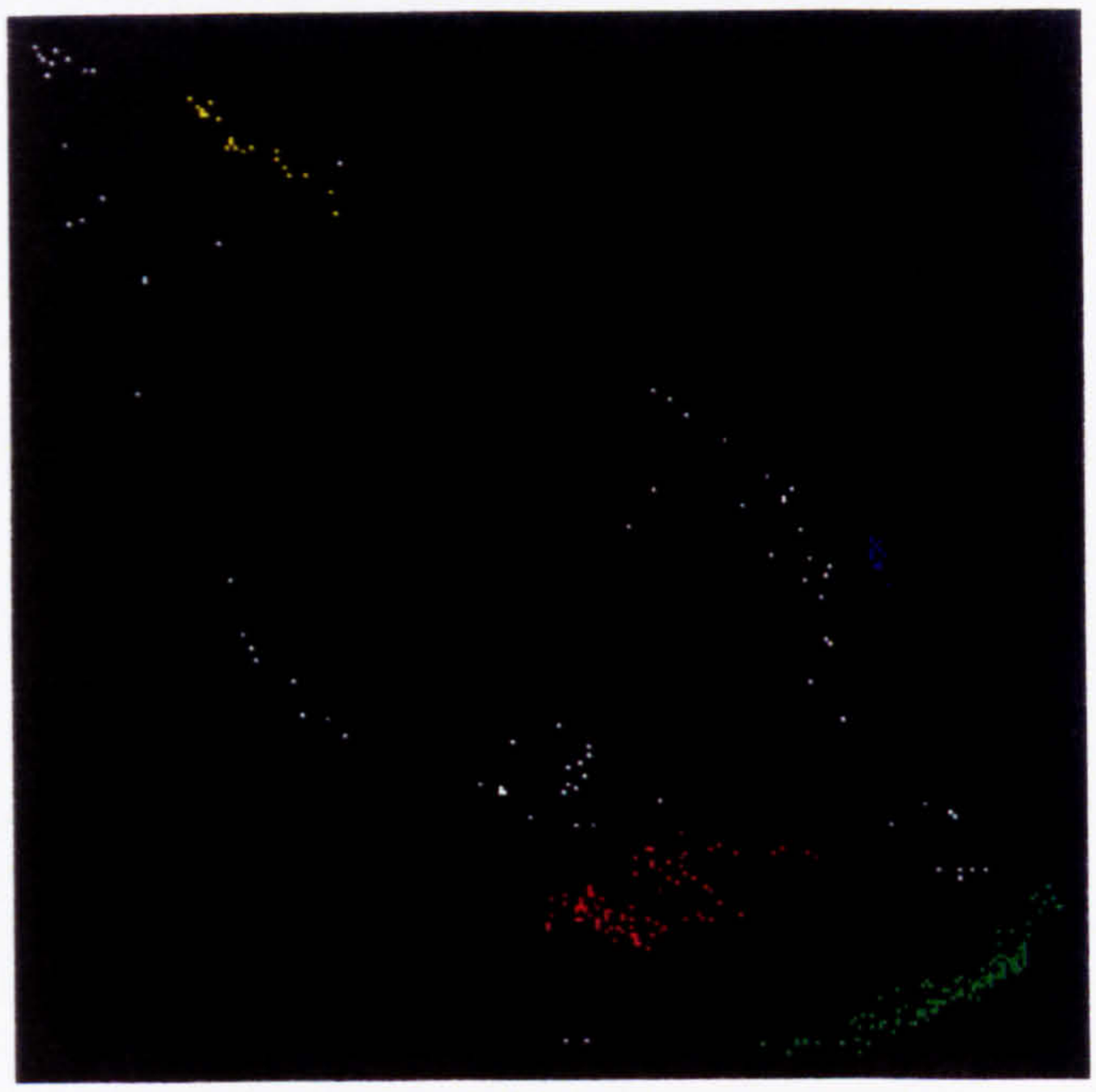


Figure 5.20 N-dimensional scatterplot of those 2m pixels identified at least once as being close to a vertex in the MNF transformed feature space.

After identifying a number of classes (in this case 10 classes), these were exported to a region of interest file where the spatial location of the corresponding image pixels was identified (Research Systems, Inc., 1995). In this case 10 classes were found corresponding to the following cover types: intertidal zone (two classes), salt marsh, white calcareous sand, sabkhah, sand bar, beach ridge, shallow water, date farm, and deep water.

Once the spatial location of the corresponding images pixels was created to match the classes identified in the 3-D scatterplot, the endmember spectra could be extracted. This was done by loading the classes onto the original reflectance image and extracting the mean reflectance spectra for all of them. The output of the endmembers spectra could then be saved in a spectral library file to be used later for the automated pixel unmixing. Figure 5.21 shows the endmembers spectra of the 10 classes identified in the airborne MEIS data mosaic covering the extreme north of Qatar. The objective now was to use these endmembers spectra to unmix the 2m and 10m spatial resolution MEIS mosaics using the linear spectral unmixing technique in ENVI software package.

Linear spectral unmixing as described by Research Systems, Inc. (1995):

> "is a mean of determining the relative abundances of materials depicted in multispectral imagery based on the materials' spectral characteristics. The reflectance at each pixel of the image is assumed to be a linear combination of the reflectance of each material (or endmember) present within the pixel."
>
> (Research Systems, Inc., 1995).

Visual inspection of the library spectra (Figure 5.21) shows some to be redundant, and it was therefore possible to simplify the library without losing information. Five endmember spectra were chosen from the library spectra representing the reflectance of intertidal zone, white calcareous sand, sabkhah, date farm, and deep water to be used in the linear spectral unmixing.

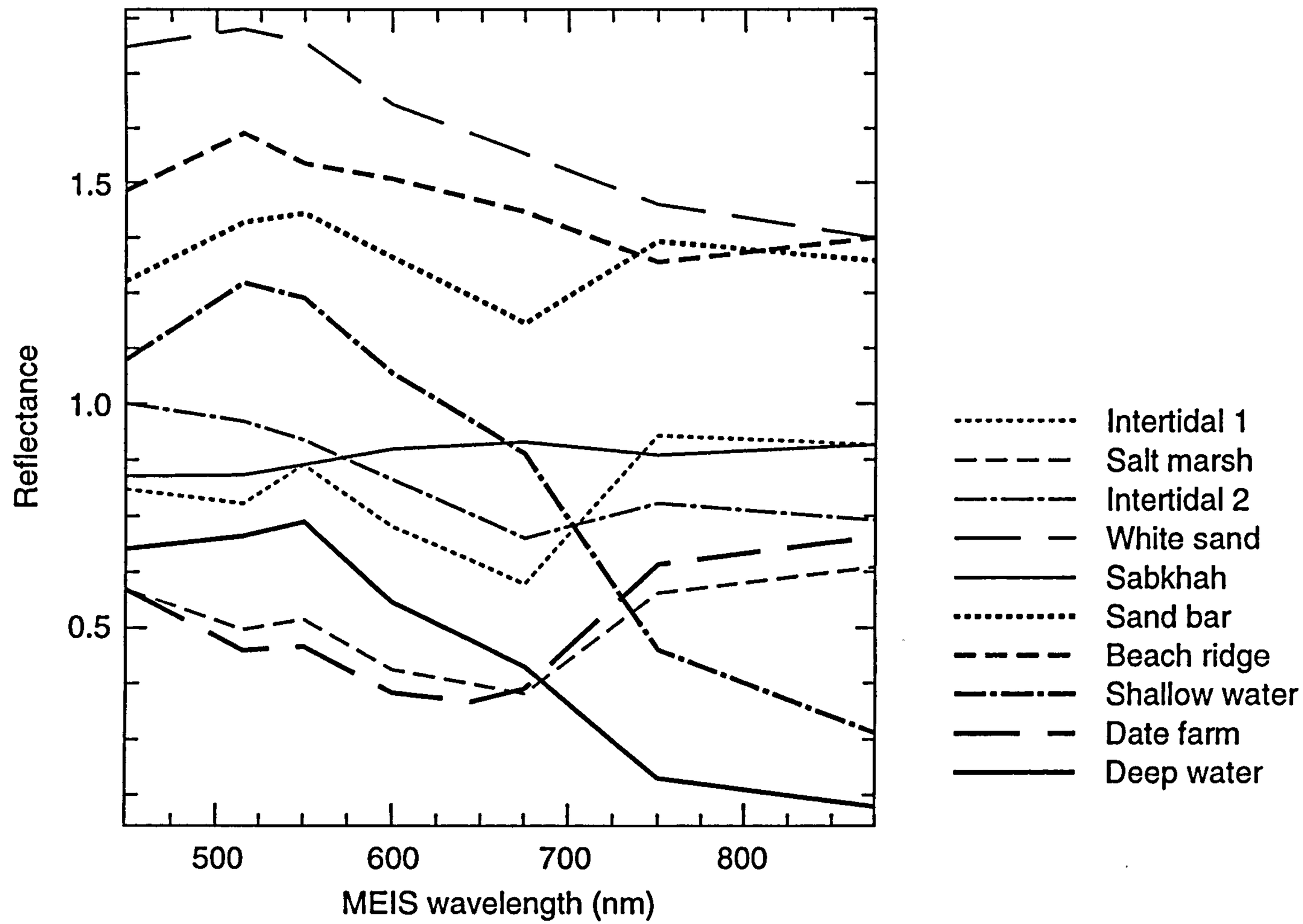


Figure 5.21 The library spectra of the endmembers identified in the transformed feature space.

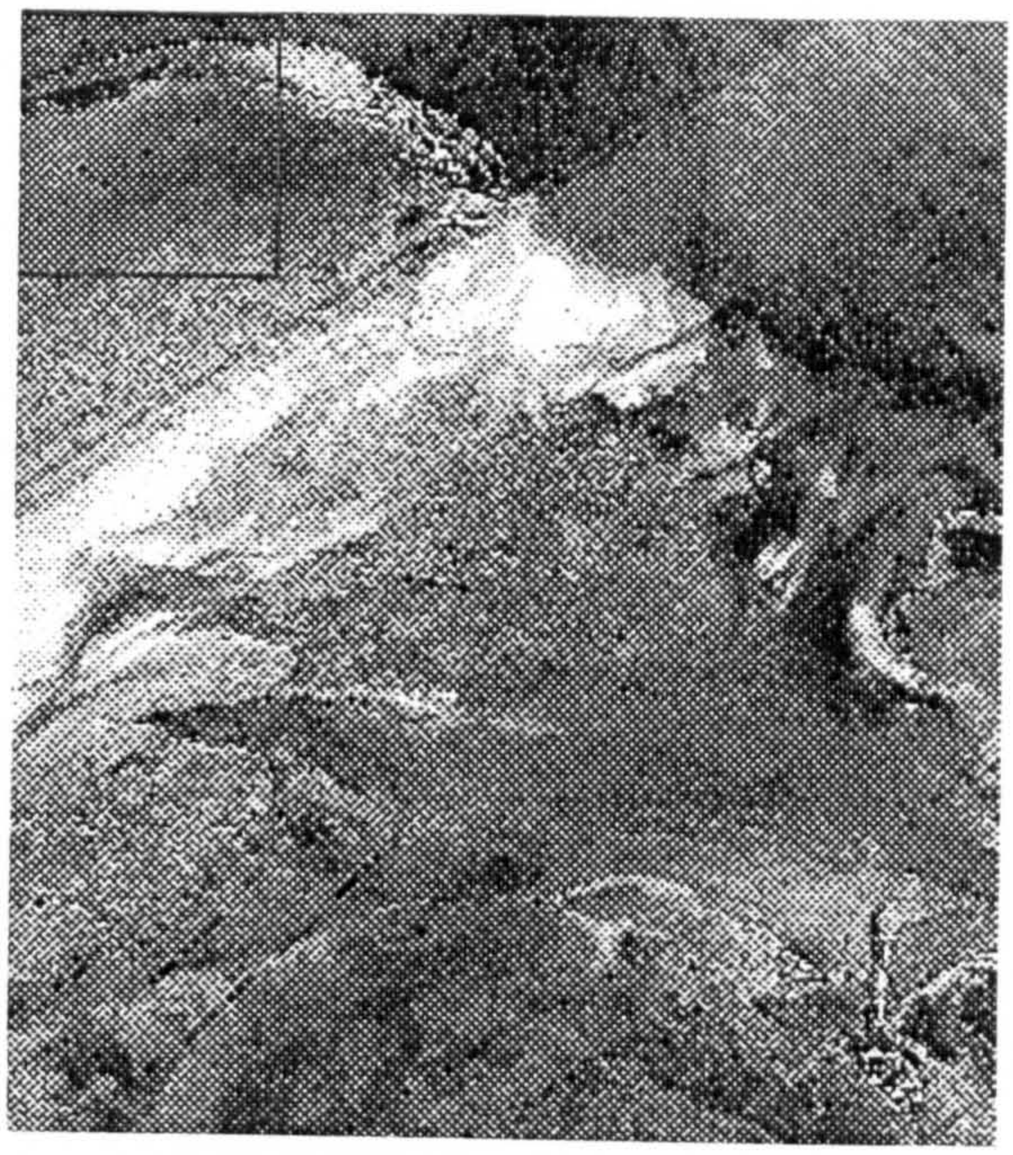
The unmixing technique was first applied to the original reflectance image (2m spatial resolution) which had been used to perform the MNF transform in the beginning of the process. The output results of the unmixing were six gray-scale images, one for each endmember spectra plus a root-mean-square (RMS) error image, where the brighter pixels represent the higher abundances for the endmember images and higher errors for the RMS error image (Research systems, Inc., 1995).

Figure 5.22 shows the six images resulting from the linear spectral unmixing and it is clear once again that they have been highly affected by the mosaicking that had been applied to the whole data. However, in the RMS error image (Figure 5.22f), the higher errors (brighter pixels) are predominantly in one flight line of the mosaic image, while the rest of the image is a shade of gray. This indicates a particular problem with one of the set of flightlines, the cause of which is unknown.

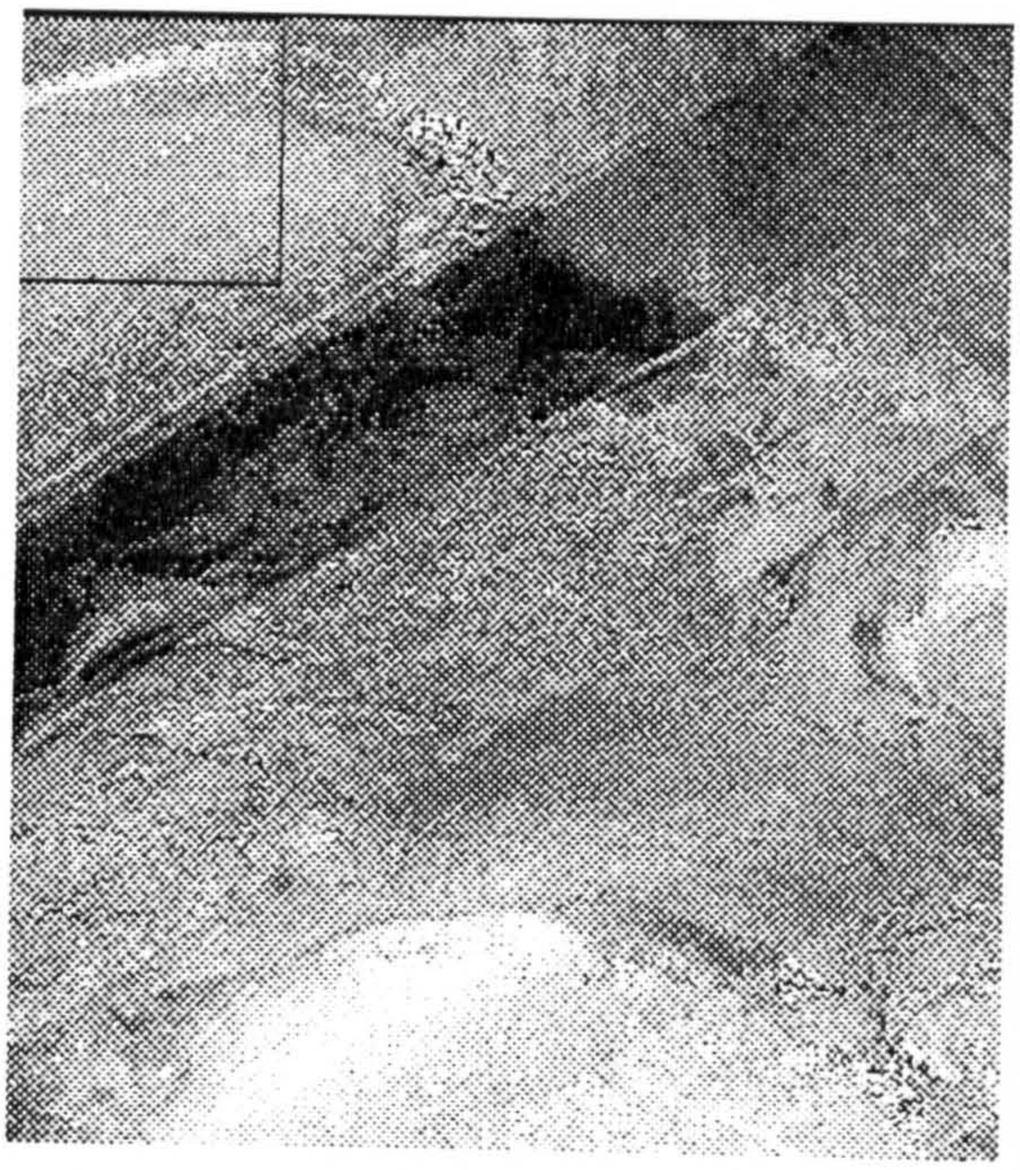
If we ignore the striping effect caused by the mosaicking process, there is strong visual evidence of the pixel unmixing process having identified correctly those areas represented by the endmembers: intertidal zone, white calcareous sand, sabkhah, green vegetation and deep water. It was therefore decided to use the same spectral library to unmix the spatially degraded MEIS data set, since this would replicate a likely future scenario in Qatar, in which 10 metre multispectral data were available from a satellite sensor over the whole of the coastal zone, and finer spatial resolution spectral data were available in a spectral library, either from ground spectra or from the present study.

a. intertidal zone

b. white calcareous sand



c. sabkhah



d. vegetation cover

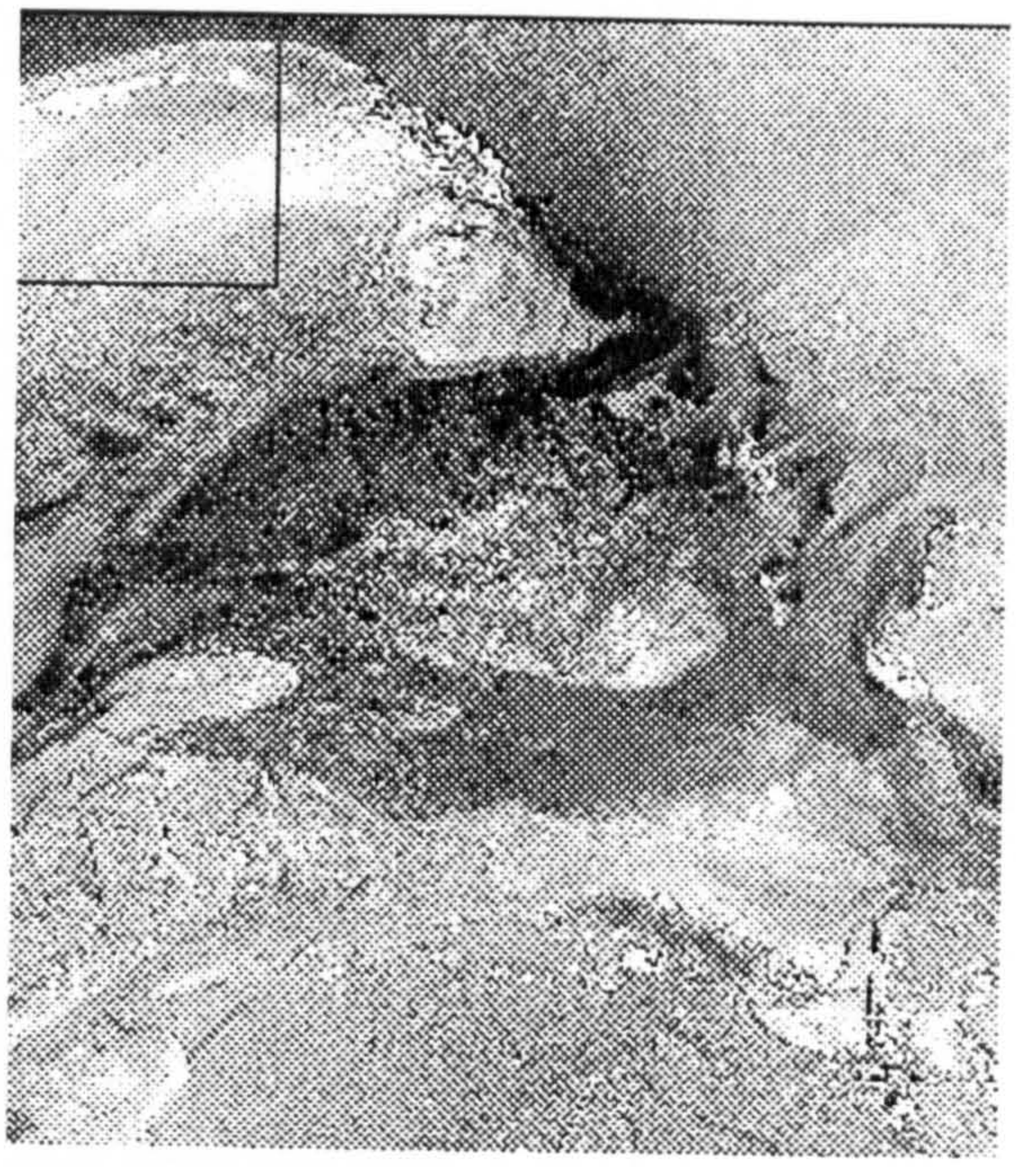
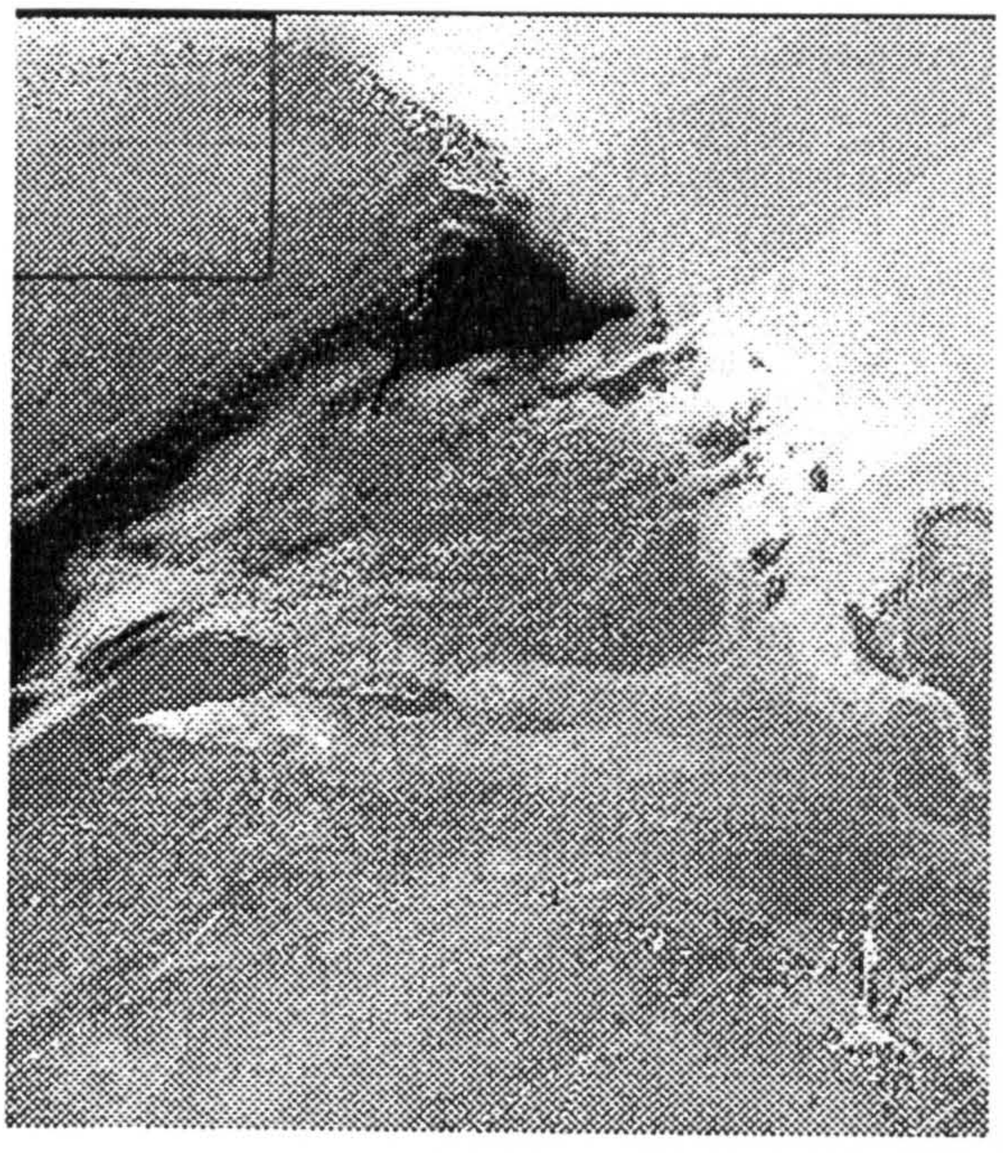
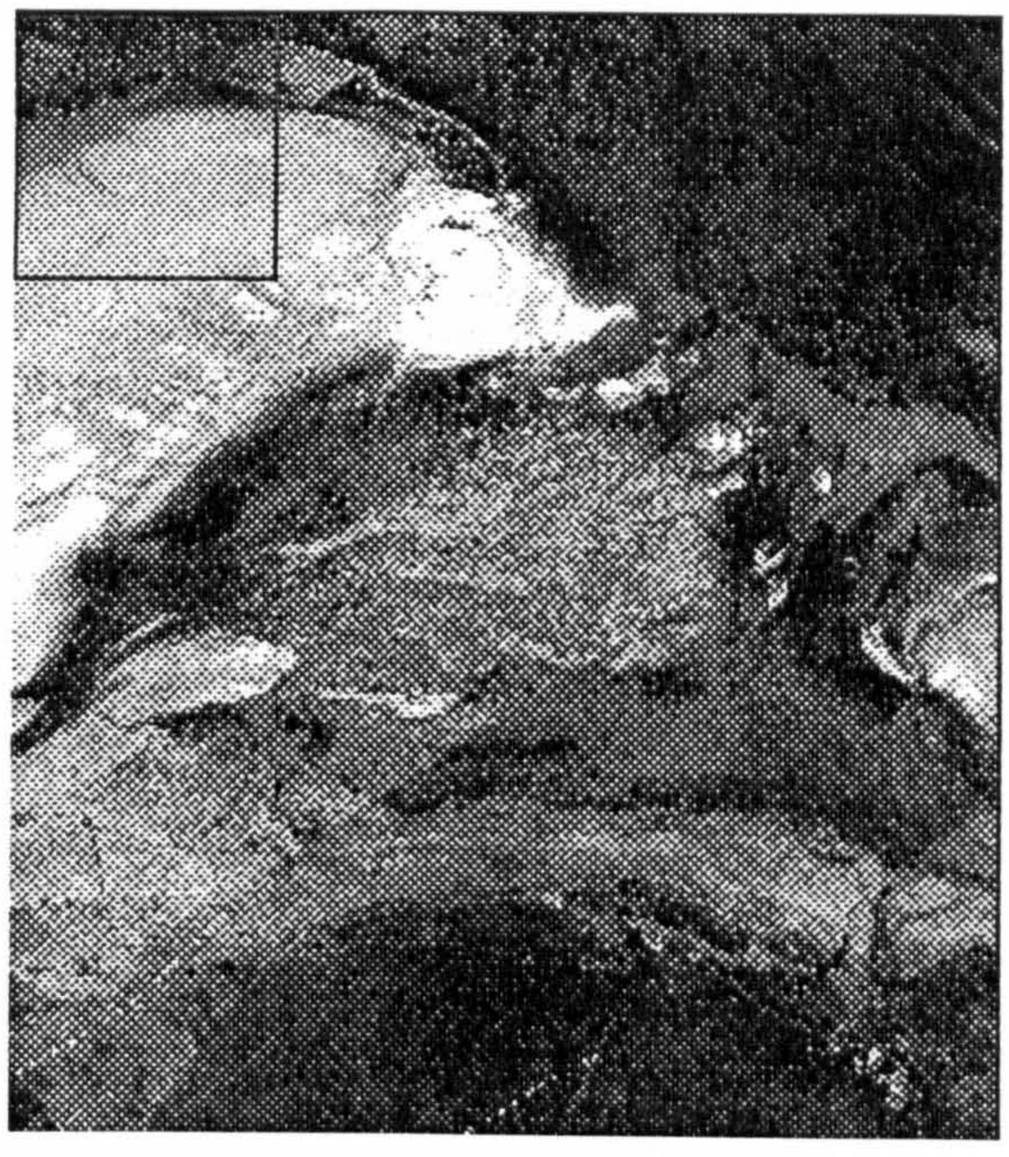


Figure 5.22 2m abundance images for five selected endmembers spectra from linear spectral unmixing analysis.

e. deep water



f. RMS error



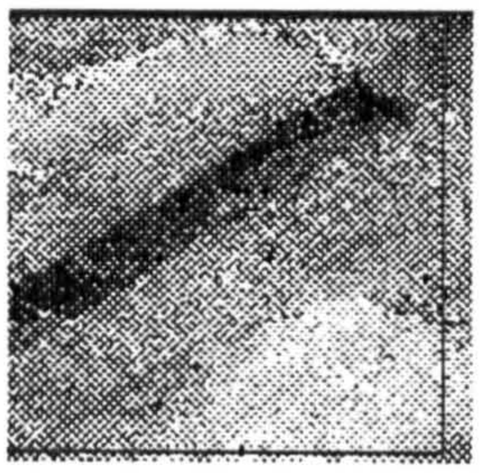
The results from this unmixing analysis of the spatially degraded MEIS data are shown in Figure 5.23. Once again, the mosaicking effect seriously affected the results, but the spatial patterns of each endmember are reasonable and accord with both the results from the automated classification of the 2 metre data and with field knowledge. It is not possible to proceed further with automated unmixing analyses of the MEIS data set because it contains serious and intractable errors, but sufficient progress has been made to demonstrate the validity of the technique when applied to multispectral data from coastal Qatar, and it is strongly recommended that a further experiment be conducted in Qatar using a more appropriate data set when one becomes available, possible from a forthcoming satellite sensor such as, IKONOS 1, ALMAZ-1B, Orbview-3, Quickbird, SPOT-5 and ALOS.

In the meantime, a useful first step towards the goal of using pixel unmixing to produce maps of the coastal zone of Qatar would be to develop further the spectral library begun during this research so that appropriate endmembers can be identified and characterised in advance of receiving the remotely sensed data to be unmixed.

a. intertidal zone

b. white calcareous sand

c. sabkhah



d. vegetation cover

e. deep water

f. RMS error

Figure 5.23 10m abundance images for five selected endmembers spectra from linear spectral unmixing analysis.

5.5.10 Visual interpretation of the airborne MEIS data set

Whilst the analysis of the MEIS data set using automated techniques was tantalising, in that it showed what could have been done if the data were of higher quality, or if greater processing power had been available, it became clear that this approach was not going to provide the information required for creation of the ESI map within the timescale for this particular piece of research. Consequently, effort was re-directed to other ways in which the MEIS data set could be used with a GIS to provide the information required.

The results from the automated analyses had shown the importance of retaining the fine spatial detail and had also suggested that little extra information would result from using all eight MEIS bands as opposed to the 'best' three. It was decided to investigate how best to use the information so clearly visible in the false colour composite images produced at the beginning of the research (e.g. Figures 5.11) as these data sets retained the full spatial information and also contained all the spectral information which was felt to be necessary to create the ESI map. Further support for this approach came from the excellent results which previous workers had achieved using visual interpretation of satellite data from Qatar (see Section 5.2), and clearly the ability to incorporate image attributes such as context and association through the power of the human eye-brain adds considerably to the classification process.

Although the MEIS false-colour composite images share many features with traditional false-colour infra-red aerial photographs, they have a number of very important advantages for the type of task described here. First, they are digital images, and can therefore be stored in a convenient form and transmitted or copied without degradation. Second, their digital nature allows them to be directly input to a GIS without an extra step of scanning or data conversion. Third, the nature of the scanning process means that the images are continuous in the along-track direction, unlike aerial photographs, each one of which covers a relatively small area of ground. Fourthly, the filters used in the MEIS sensor can be changed to provide a different set of spectral bands, unlike false-colour infra-red film which has fixed spectral sensitivity. Of course, there are also some disadvantages compared with aerial photographs, notably the lack of stereo imaging, but the point is that the MEIS composite images are not simply glorified aerial photographs. They are a new source of digital image data and should be treated as such.

During the later stages of this research a number of developments in digital aerial photography have been reported in the literature (e.g. Maas and Kersten, 1997; Anderson *et al.*, 1997), and the work described here using images from the MEIS sensor relates directly to these developments in digital imaging more generally.

Like the automated approach to image classification, the visual approach quickly ran into problems of data storage. Each MEIS false-colour mosaic covering 10 km x 10 km occupied over 70 Mb of disk space, severely limiting the number of scenes that could be kept on-line at any one time.

5.5.11 Image compression techniques applied to the airborne MEIS data

In order to reduce the demand for disk space a number of different ways of compressing the MEIS images were investigated to test how efficient they were with this type of data and to determine whether the loss of information was acceptable for the purpose of ESI map production. Two different compression techniques developed for continuous tone images were tried: GIF compression and JPEG compression (Figure 5.24).

GIF compression is only applicable to 8-bit images, so the 24-bit MEIS composites had first to be converted to 8-bit paletted images, implying a loss of colour resolution. The 8-bit paletted images were then compressed using the GIF89a algorithm which preserves all the spatial information (Handmade Software, Inc., 1994). GIF compression is also widely used for storing 8 bit scanned or digitized images. Therefore it is ideal to test and compare these two compression methods on the MEIS airborne multispectral images.

JPEG compression can be applied to full 24-bit images, so the colour resolution is preserved, but it is a 'lossy' compression technique in that some of the spatial detail is lost. The user has control over the degree of information loss through the 'Quality' factor which typically ranges from 0 - 100, and the compression is done in such a way that the visual appearance of the image is least affected.

At the same time that the MEIS images used in this study were being processed using the JPEG compression technique, a paper was published by Lammi and Sarjakoski (1995) in which they described application of the technique to small digitized aerial colour images. Their test concentrated on the geometric degradation of the compression process on the digital images. Their result and experience showed that the JPEG algorithm is a good choice for image compression as it does not introduce significant degradation in the visual or geometric quality of the image for compression ratios of up to 1:10. The higher the compression ratio the more geometric degradation occurred.

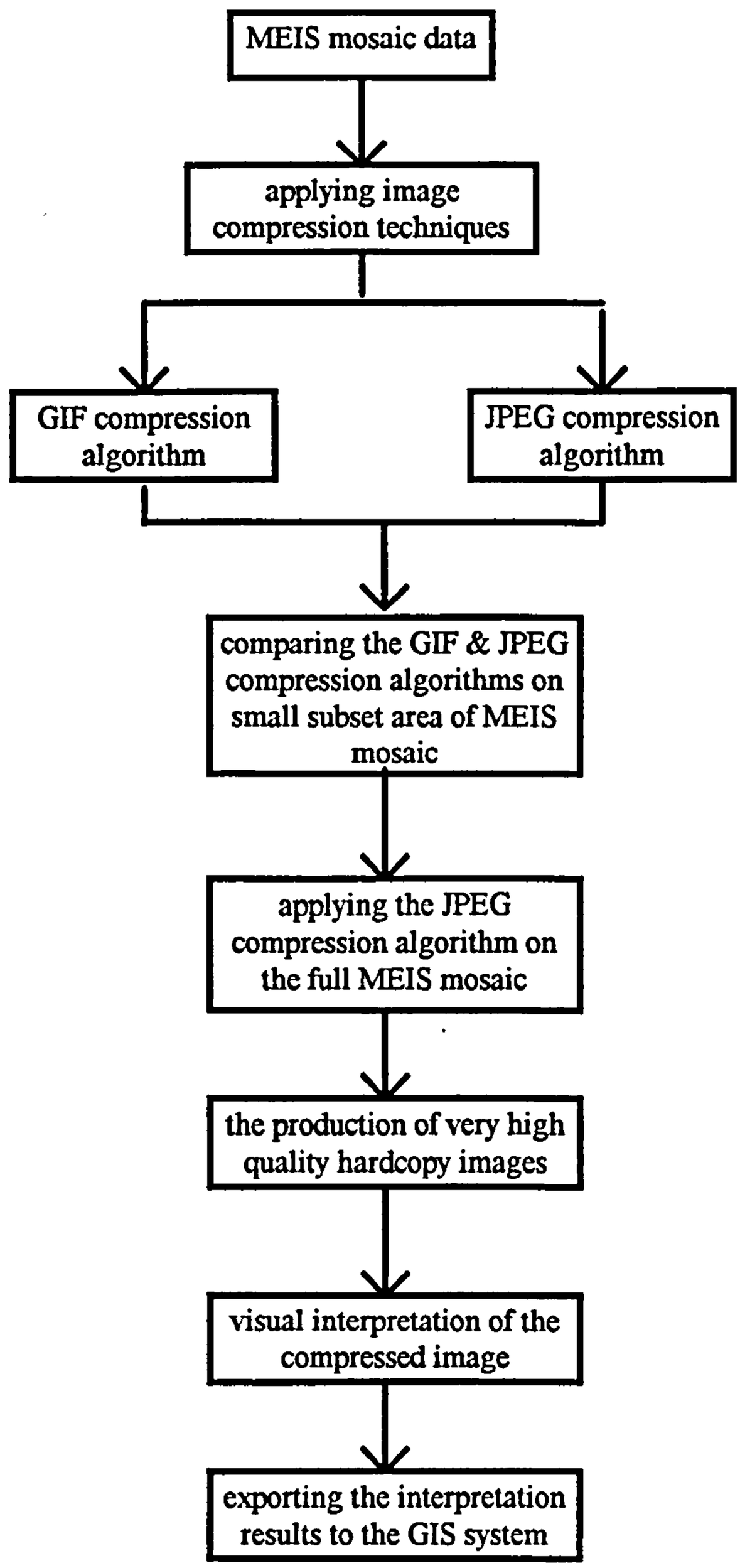


Figure 5.24 The flow chart of the image compression methods applied to the MEIS mosaic data.

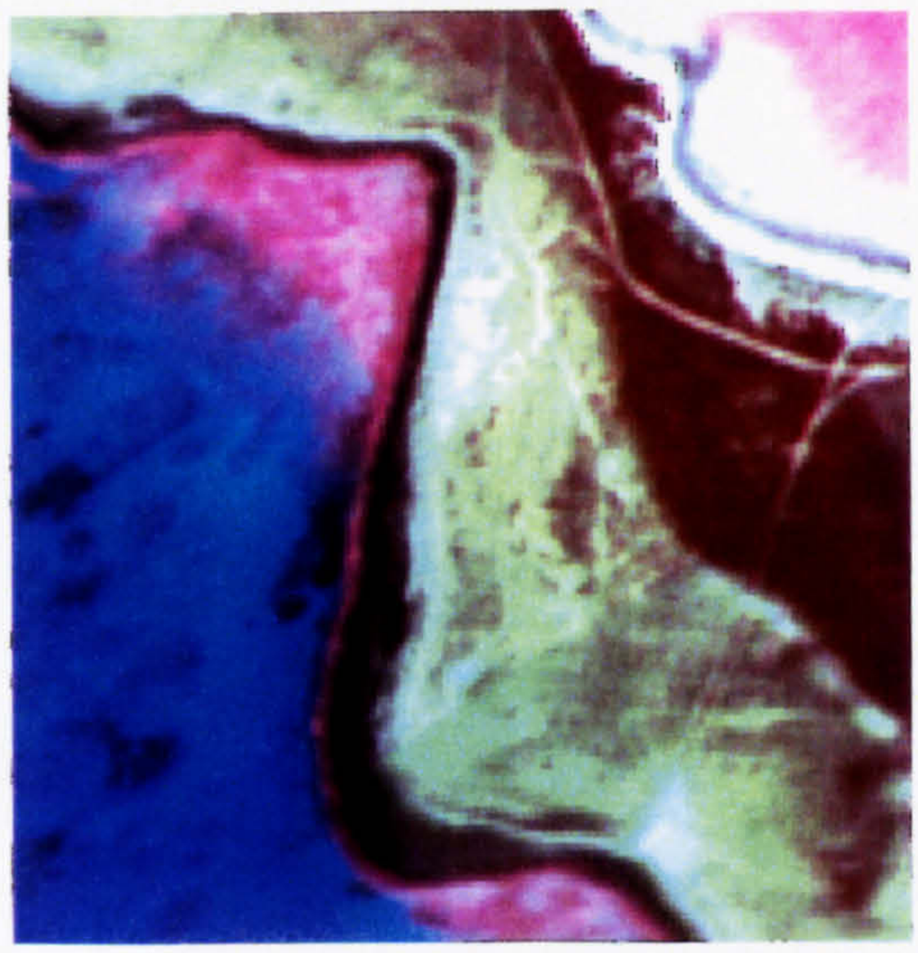
5.5.12 Comparing the JPEG and GIF compression algorithms on a small subset area of the airborne MEIS data

A very small subset area was first generated from the MEIS image covering the extreme north of Qatar in order to carry out the image compression test and see the degradation effect before applying it to the whole image. The subset covered a small area of the southern part of Ras Rakan island, northern Qatar, and its surrounding intertidal and shallow water areas (Figure 5.25a).

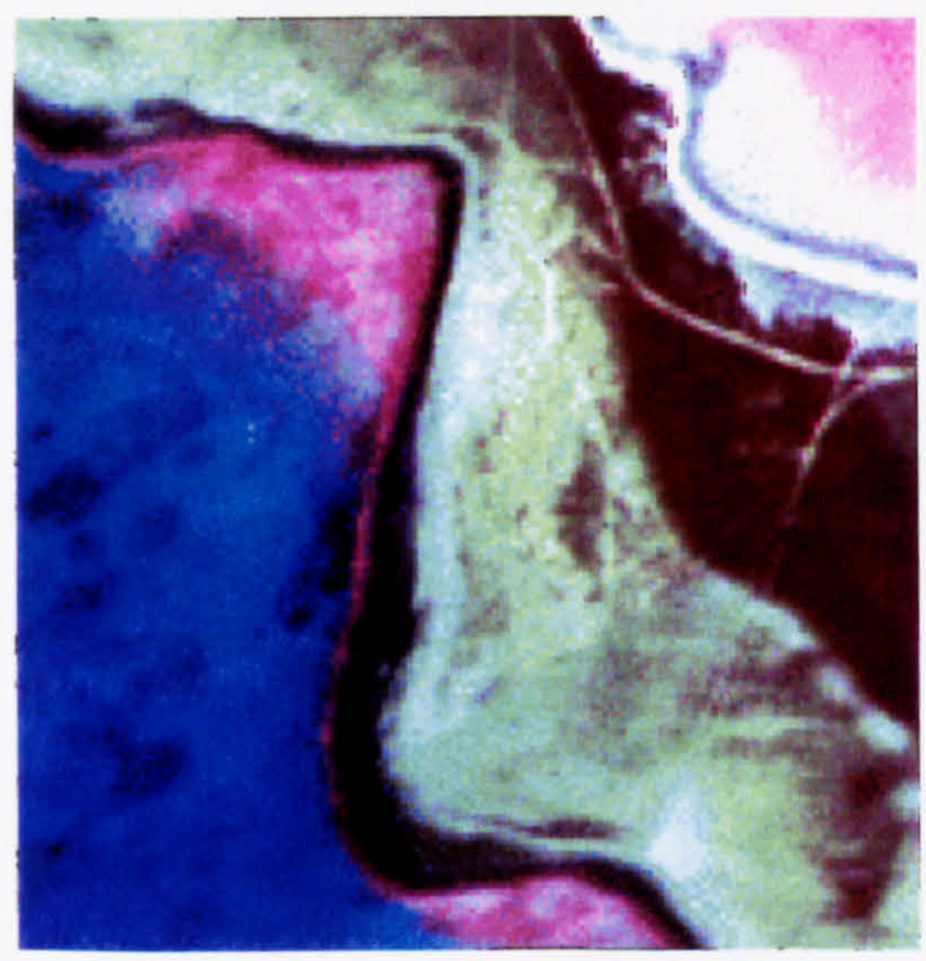
ERDAS IMAGINE software was used to generate this subset using three bands of MEIS data (RGB/328, the same bands and colour used in the classification techniques). The subset was then contrast stretched and saved as another file using the appropriate look-up table in order to keep all bands of the subset in the right order as displayed on the screen (RGB/328). The subset file was then exported to a PC where the image compression software (Image Alchemy) was available.

GIF compression was applied to the test subset using Image Alchemy. The resultant image appeared to be slightly more grainy (Figure 5.25b) than the original image. Individual pixels are clearly visible in the intertidal and shallow water areas (the left section of the image) due to the compression effects. This made the image look more blocky.

a. the original image.



b. after applying the GIF compression.



c. after applying the JPEG compression.

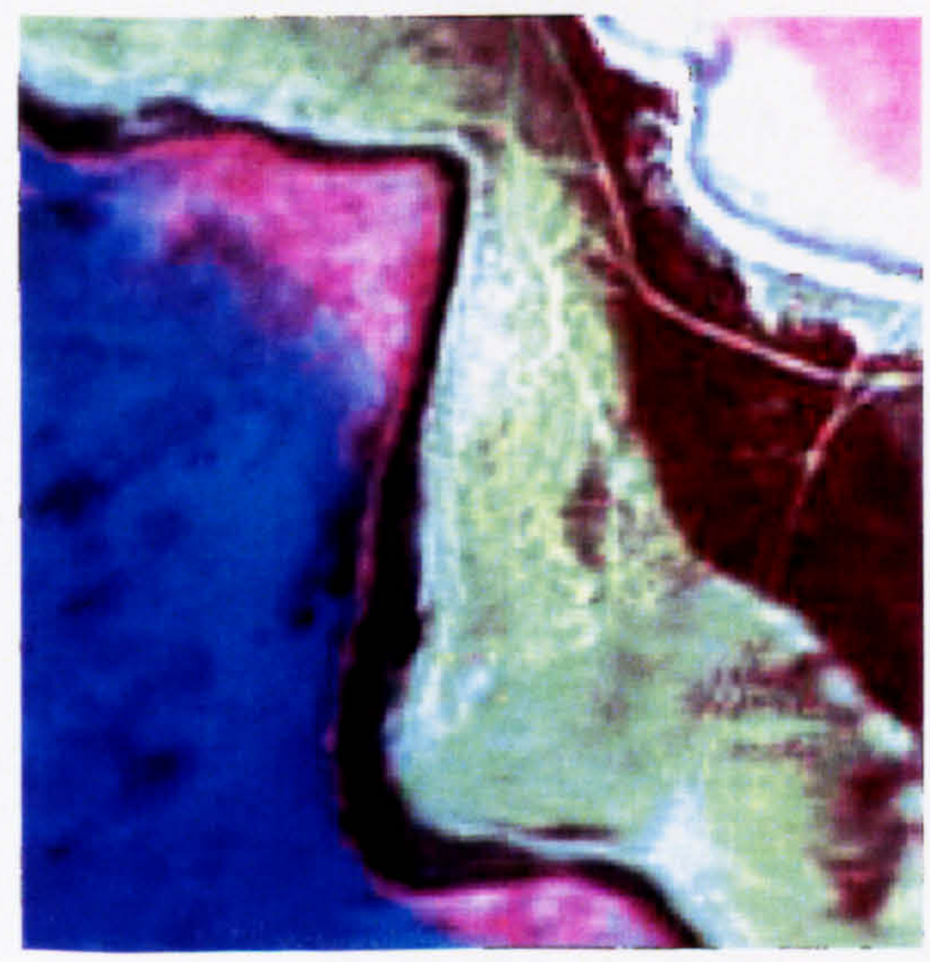


Figure 5.25 A small subset area of MEIS data of the southern part of Ras Rakan island (extreme north of Qatar) used in the GIF and JPEG compression.

JPEG compression was also applied to the test subset. The JPEG algorithm provides four possibilities of operation or encoding as described here by Lammi and Sarjakoski:

> "The JPEG standard contain four modes of operation : sequential encoding, progressive encoding, lossless encoding, and hierarchical encoding. The sequential and progressive encodings are based on the discrete cosine transform. Both of these modes are lossy encoding techniques, i.e., some information is lost during the compression process. In the sequential mode, each image component is handled in a single left-to-right, top-to-bottom scan while, in the progressive mode, the image is handled in multiple scans. In the lossless encoding, the image is compressed so that the exact recovery of the original image is guaranteed. The lossless mode of JPEG is based on a predictive method. The hierarchical mode encodes the image at multiple spatial resolutions using either the DCT-based compression or the lossless mode."
>
> (Lammi and Sarjakoski, 1995)

The MEIS data were subjected to JPEG baseline sequential encoding. This is a basic compression scheme for straightforward use and consists of a series of mathematical operations including colour space conversion, discrete cosine transform, quantization, and entropy coding (Handmade Software, Inc., 1994 ; Lammi and Sarjakoski, 1995). The resultant image (Figure 5.25c) is very similar to the original image and it needs very detailed inspection before any difference between it and the original can be seen.

The conclusion of this test was that JPEG compression was more suited to reducing the size of the MEIS colour composites than GIF compression. The loss of colour information caused by the reduction from 24-bits to 8-bits which is inherent in the GIF compression caused a greater loss of useful information than the 'lossy' nature of the JPEG compression.

5.5.13 Applying the JPEG compression algorithm on the full mosaics of the airborne MEIS data

Figure 5.26 shows the resultant image after applying the JPEG compression on the full mosaic covering the extreme north of Qatar coastal zone. The compression algorithm has removed the redundancy from the original image thus reducing the size of the output file significantly. Figure 5.27 compares the file sizes of each of the products produced during this investigation. It is clear that the JPEG compression technique achieves the greatest saving in disk space while retaining all the information required to create the ESI map. In addition to their benefits for image storage, the JPEG compressed images are easier to create hardcopy products from as the decompression is done by the software at the same time that the image is prepared for display or printing out. Thus, ordinary PC-based graphics software such as Corel Draw or Adobe Photoshop can read the JPEG compressed files and create high quality colour prints, unlike the original uncompressed files which required specialist software such as ERDAS IMAGINE running on a Unix platform.

The production of high quality hardcopy from the compressed images made the visual interpretation and mapping of significant coastal features and land cover more possible. Looking through the shallow coastal water in the image (Figure 5.28) the oil tar from the last oil spills in the Gulf in January 1991 can be seen very clearly. The spatial resolution of the sensor is very important here for mapping these significant oil tar features. Field verification took place in northern Qatar to check this result. Underwater diving with a camera and a GPS system were used to verify the presence of oil tar on the bottom of the shallow coastal water.

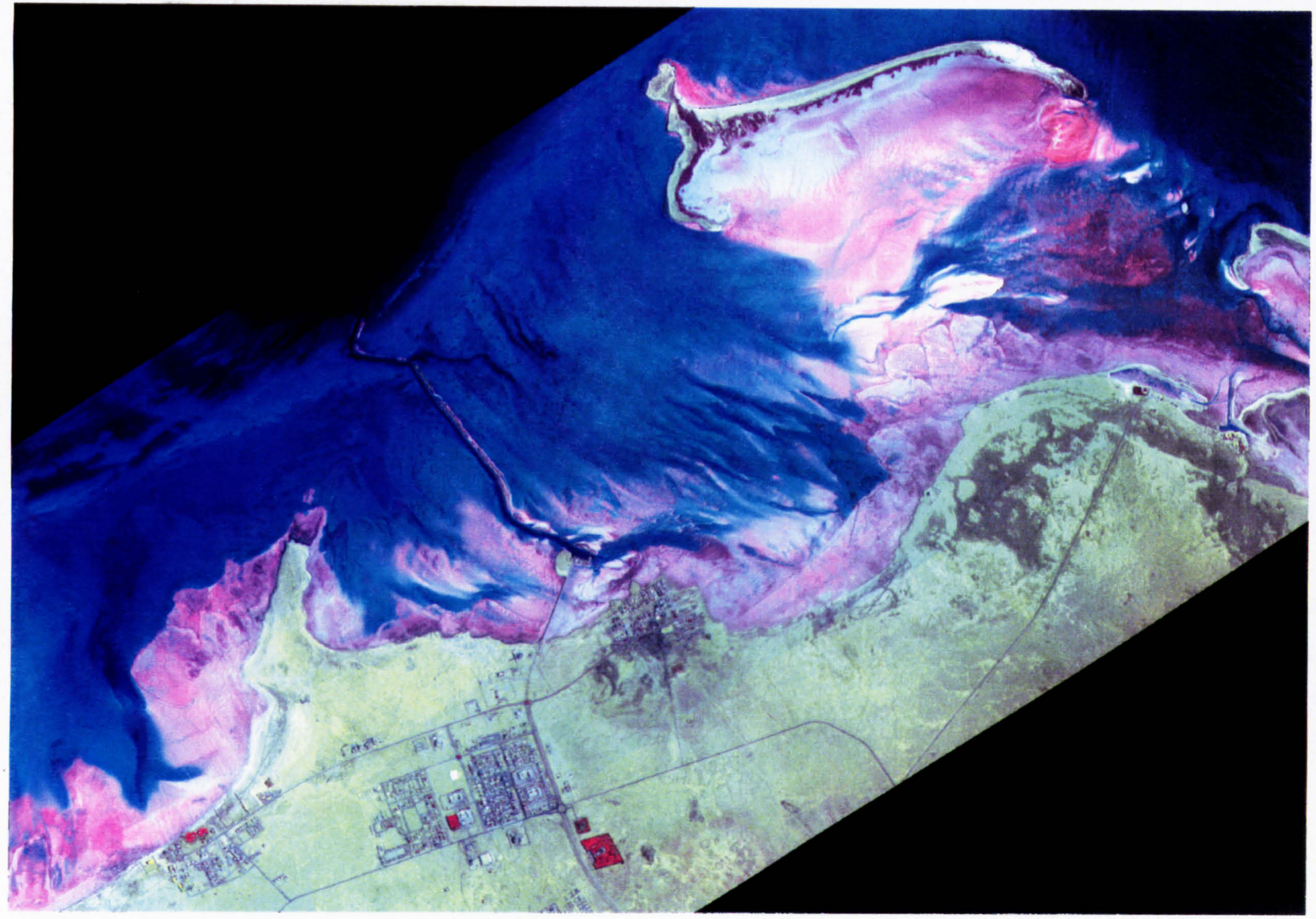


Figure 5.26 MEIS mosaic covering the extreme north of the coastal zone of Qatar after applying the JPEG compression.

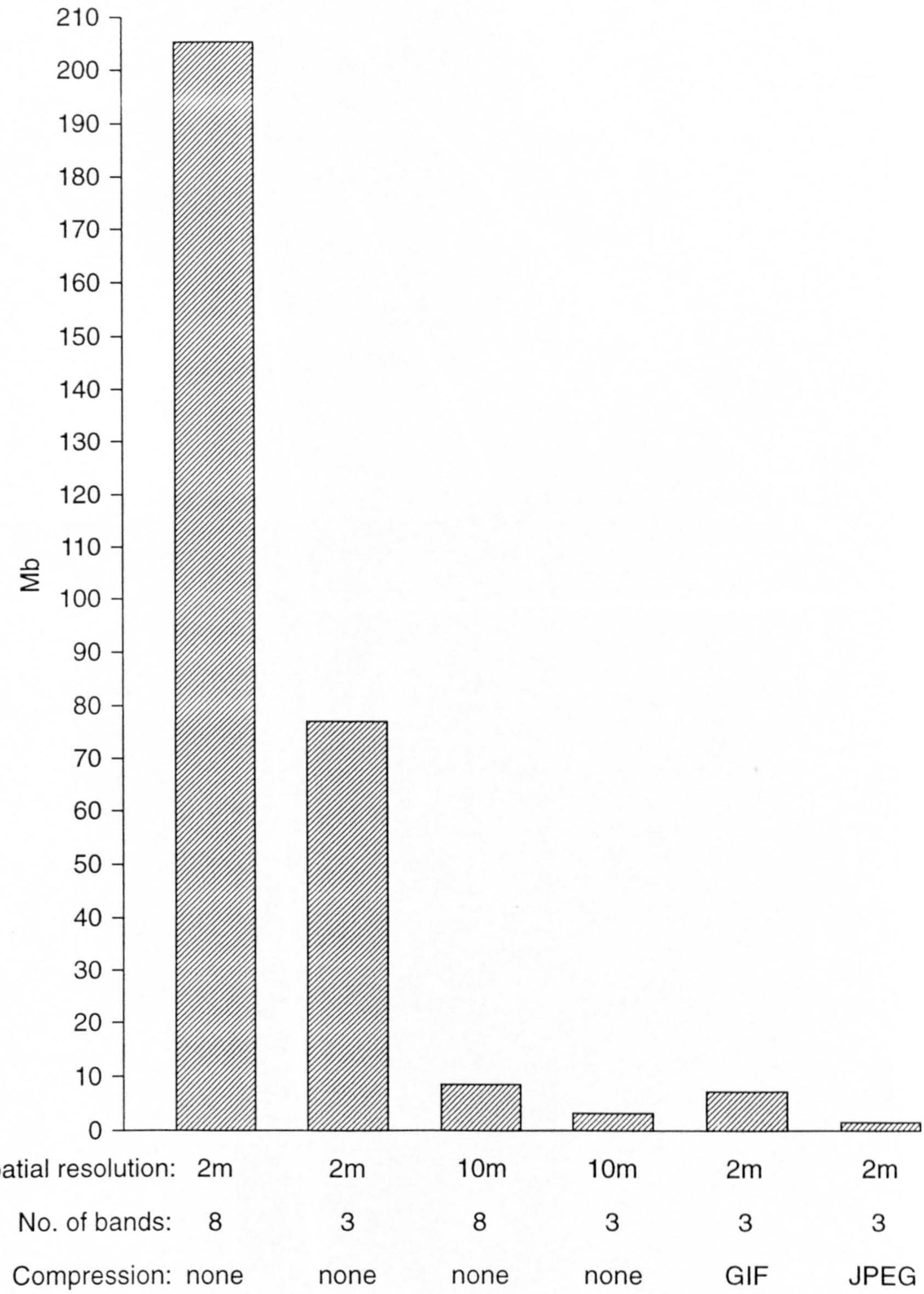


Figure 5.27 Storage requirement of a single 10km x 10km mosaic.

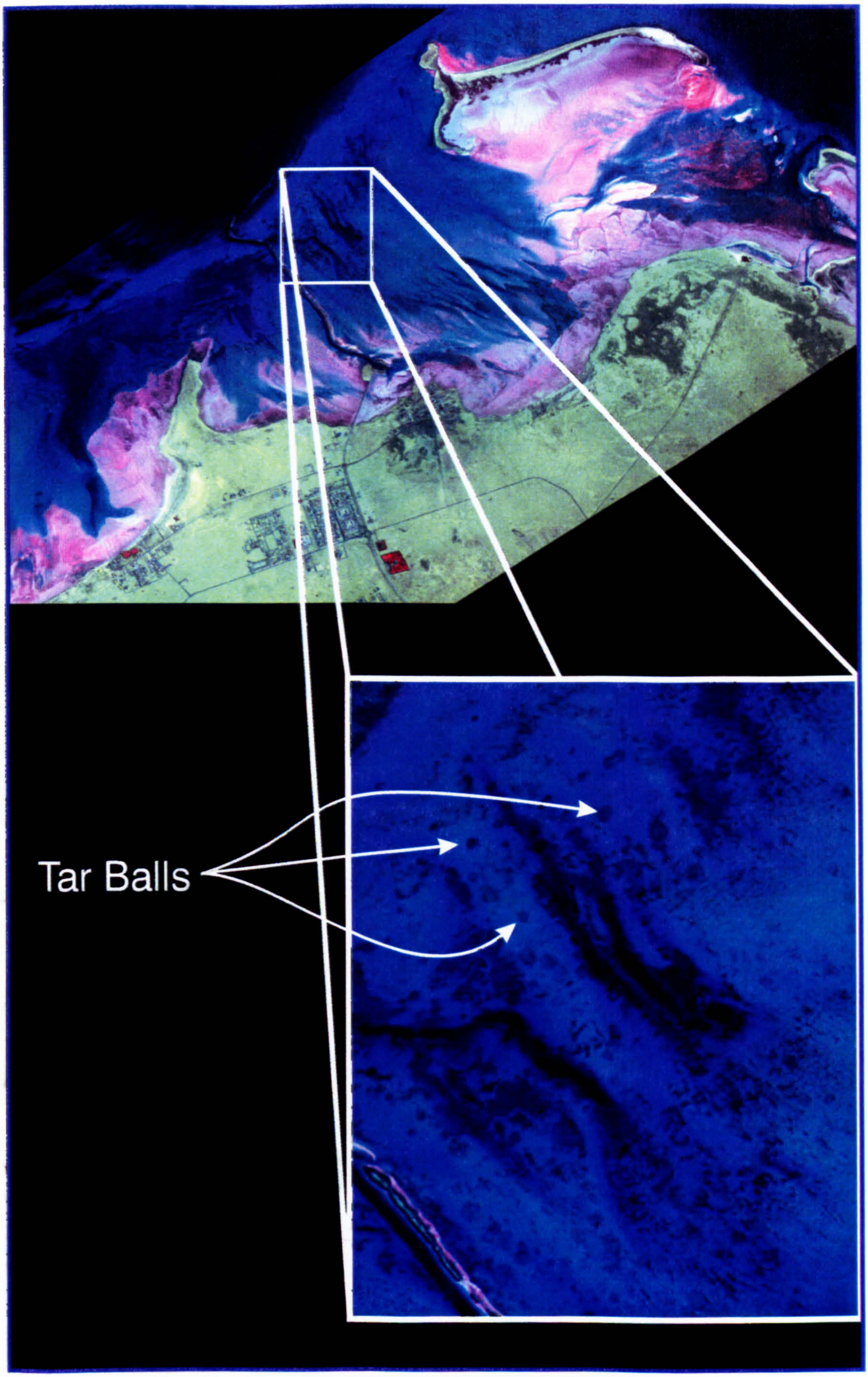


Figure 5.28 The compressed MEIS image showing very clearly oil tar in the shallow water of extreme north of Qatar from the last oil spills in the Arabian Gulf in 1991.

Most of the light chemical components of the crude oil are evaporated by the sun which makes the oil thicker causing it to break into small pieces, and eventually form oil tar. The oil tar was carried out by the wind and surface currents in the Gulf to the shallow coastal water of northern Qatar. This area is known to be a high energy and sediment movement area, therefore, when the oil tar reached the area a lot of sediments stuck to it making the tar balls heavy so that they can not float on the surface of the water. As a result most of the oil tar sank in the shallow water covering all types of life beneath. Some of the tar balls still can reach the shore line of northern Qatar and can make very severe damage like what happened during the Gulf War.

Figure 5.29 shows the final map of the extreme north of Qatar coastal zone resulting from the visual interpretation of the compressed image (Figure 5.26). Areas which are very sensitive to oil spills such as the salt marsh, seagrass, and intertidal area were readily mapped. Notice that the oil tar and shallow water are mapped as one class because the oil tar is widely scattered in the shallow water area. Therefore, mapping oil tar as a separate class would make the final map too complicated.

Having successfully used the JPEG compression technique to produce the land cover map of the northern mosaic, the method was applied to a second 10 km x 10 km mosaic, this time from an area in northeastern Qatar (Figure 5.30). The differences in illumination intensity between adjacent flight lines which caused major problems with the automated classification are very clear in this image. However, through visual interpretation of the compressed composite it was possible to allow for this defect and produce an accurate and comprehensive map. The northeastern coastal zone of Qatar is very complicated and is sensitive not only to oil spill but also to human activities and development. The human pressure on the area is clear from the number of jetties and roads crossing the sabkhahs and salt marshes of the area. You can see on the other hand the growth of mangroves in bright red colour taking place on the muddy sediments of the area. Using the compressed MEIS composites it was possible to map all these sensitive and small details of the area in Figure 5.31.

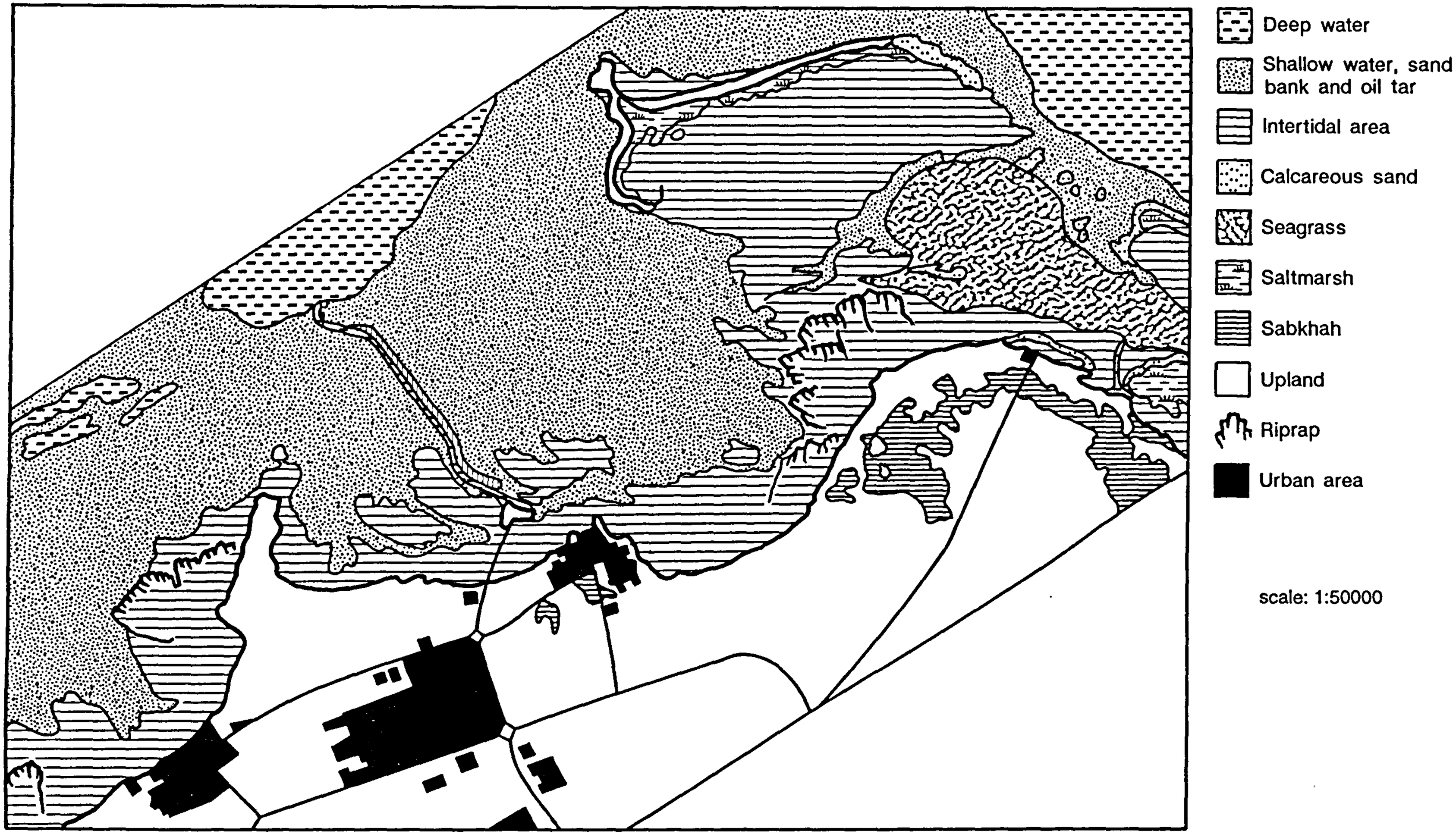


Figure 5.29 The visual interpretation map of the extreme north of the coastal zone of Qatar.

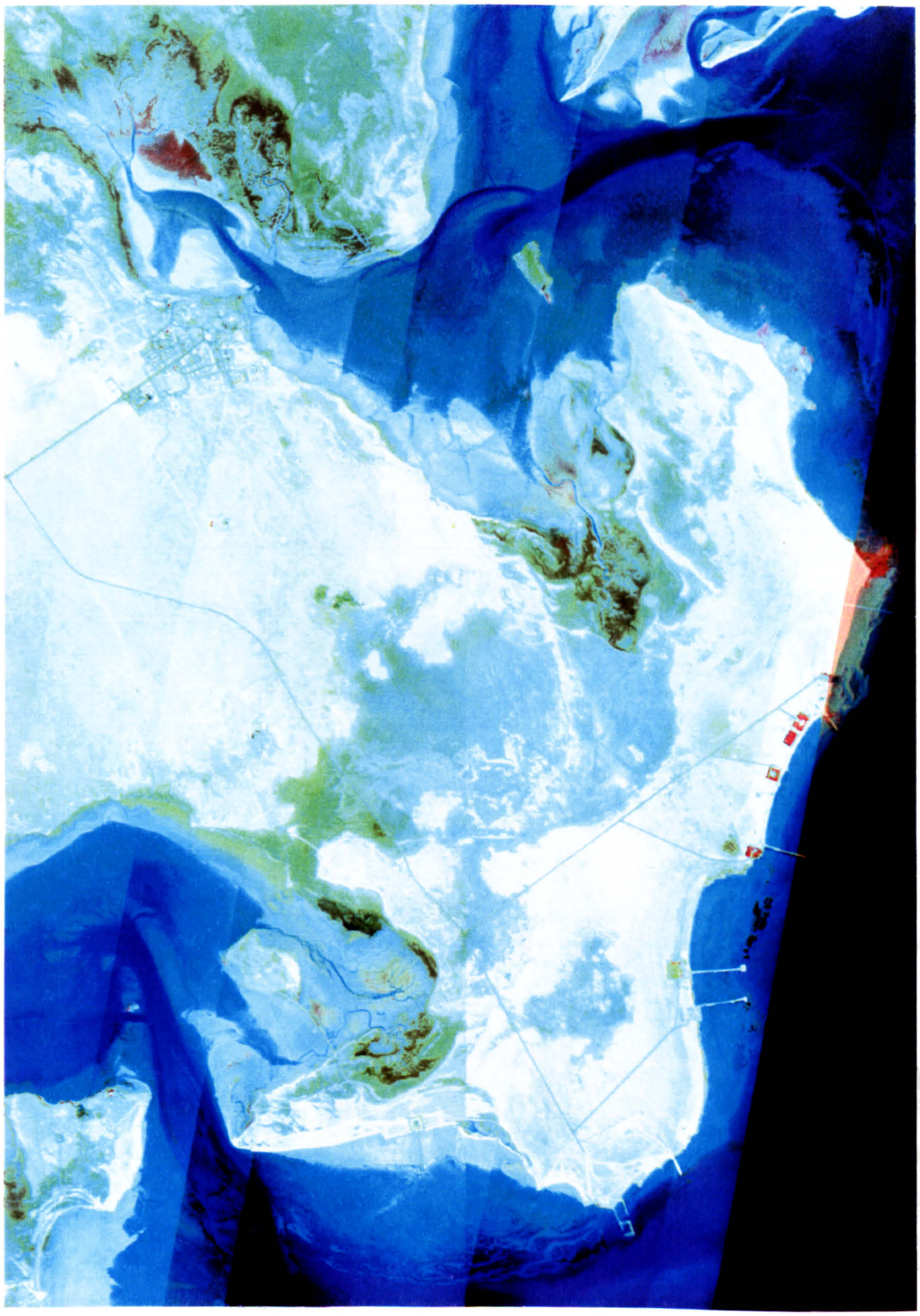


Figure 5.30 MEIS mosaic covering the northeastern coastal zone of Qatar after applying the JPEG compression.

Figure 5.31 The visual interpretation map of the northeastern coastal zone of Qatar.

In summary, the JPEG compression algorithm worked very well for the airborne MEIS digital data covering the coastal zone of Qatar. The compression algorithm removed the redundancy from the original image which reduced the size of the output file enormously and produced very high quality images and printed hardcopy. Very detailed and accurate maps of the sensitive coastal resources were produced from the compressed MEIS images using well-established methods of human visual interpretation despite the original data set being flawed in various ways.

5.6 CONCLUSION

In conclusion, remote sensing provides the only practical means of mapping and monitoring changes over large areas of the Earth's surface and the technique is well-suited to arid and semi-arid areas of the world where low cloud cover allows the use of sensors operating in the optical region. Remotely sensed data have been a major source of information in Qatar and are likely to continue to be in the future for the diverse nearshore marine and coastal environments. Research applications world wide of many of the applied fields have turned increasingly to remote sensing for a partial and/or full solution. Previous studies have proved that information derived from remotely sensed data are more cost-effective and up-to-date than information compiled from field measurements.

Therefore, the role of remote sensing in Qatar is to provide the practical means of mapping and monitoring changes over the Qatari lands and the Gulf's waters. The present medium resolution satellite systems such as Landsat, SPOT, ERS and RADARSAT are the perfect solution for regional compilations. They are useful for mapping and monitoring broad areas of Qatar and the Gulf for example for: geological structures and lithology, water-land boundaries, coastline changes, oil spill detection and changes on the Gulf's waters surface. However, systems with fine spatial resolution are needed for detailed mapping and monitoring of the coastal zone.

The present high spatial resolution airborne MEIS data covering the whole coastal zone of Qatar provides a very good example of such fine spatial resolution system for detailed mapping. The 10 km x 10 km geometrically corrected MEIS tiles are a suitable ground coverage of fine spatial resolution data to be used in current image processing work stations. The only two disadvantages of the MEIS data were the striping caused by the differences in brightness between adjacent flightlines, and blurring (double-vision) effect caused by the system, which had affected the automated analyses applied to the data. The result from the automated analyses showed the importance of retaining the fine spatial detail and also suggested that little extra information would result from using all eight MEIS bands as opposed to the "best" three. The visual interpretation approach of the compressed MEIS images worked very well for the present airborne MEIS digital data covering the whole coastal zone of Qatar (Figure 5.32). The compression algorithm removed the redundancy from the original image which reduced the size of the output file enormously and produced very high quality images and printed hardcopy. Very detailed and accurate maps of the sensitive coastal resources were produced from the compressed MEIS images using well-established methods of human visual interpretation despite the original data set being flawed in various ways.

In addition, the compression technique provides very good archive method for the 233 mosaic tiles of MEIS digital data, in order to facilitate the quick access to such large volume of digital data when needed for oil spill emergency response. Moreover, a useful first step towards the goal of using pixel unmixing to produce maps of the coastal zone of Qatar would be to develop further the spectral library begun during this research so that appropriate endmembers can be identified and characterised in advance of receiving the remotely sensed data to be unmixed. Spectral information of surface materials in Qatar can be obtained from field measurement and MEIS digital data.

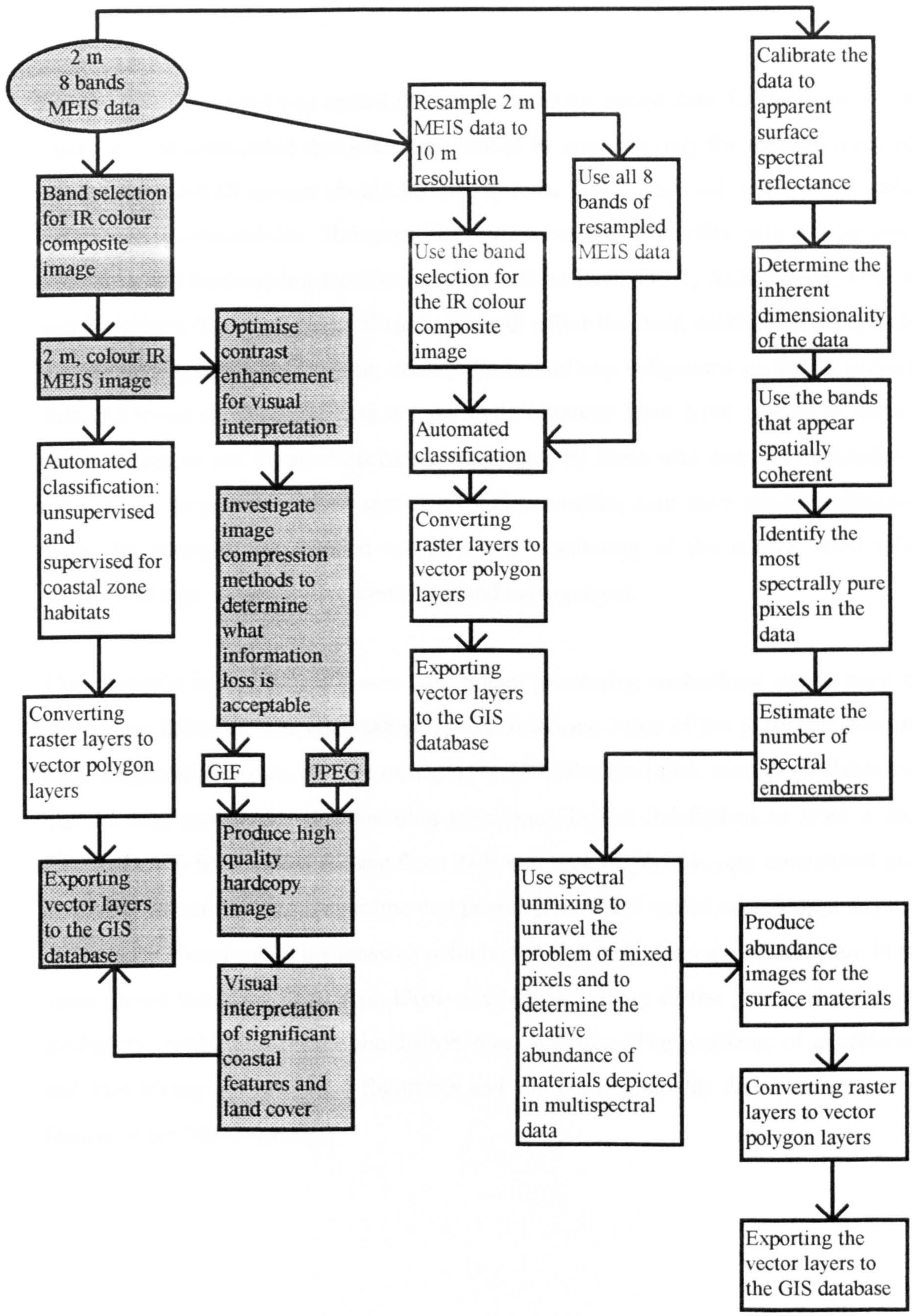


Figure 5.32 General flow chart showing the various processing techniques applied to the MEIS data to produce a land cover map of the coastal habitats in northern Qatar, shaded boxes indicate the most successful path.

For the future acquired fine spatial resolution remotely sensed data for the coastal zone of Qatar, it is recommended that such data should be acquired only for selected areas of the coastal zone. MEIS system should be used for the future acquired fine spatial resolution data for data compatibility. However, fine spatial resolution satellite data will be available soon from the forthcoming satellite systems such as IKONOS 1, ALMAZ-1B, Orbview-3 and Quickbird. The availability of such data will offset the main problem of using airborne remote sensing in the Gulf region, namely the lack of any indigenous system to acquire the data. Airborne multispectral data are currently obtained from hired foreign systems, and this is expensive and involves decisions being made by those who may not be familiar with the area or its problems. Fine spatial resolution satellite data have many applications in Qatar for example for: detailed mapping and monitoring of the coastal zone habitats, offshore oil rigs, urban development, and land management.

The advances in computing power and image processing technology which have taken place since the work was undertaken should overcome some of the problems faced in the early stages of the research. For example, in 1993 the hard disk storage available on-line was 90 Mb, enough for the raw data from one tile, but insufficient to store a second. Reading a 200 Mb merged mosaic from its 8 mm tape required a very convoluted process involving several PC and mainframe computer systems and could take several days in the early stages. Fortunately, the massive reduction in the cost of computer hardware in recent years means that data storage problems are largely a thing of the past, and even quite a modest PC could now handle the 50 Mb tiles with ease. The problems of georeferencing and mosaicking the individual flightlines and the blurring in this data set were simply a feature of the MEIS sensor.

A problem which remains concerns the classification of images containing very large numbers of polygons. In the present example many of these were real components of the scene such as individual bushes and their shadows or small areas of rock. The components were not extensive enough to extract training site data from, but were sufficiently dominant to distort the per pixel classifiers used in the study. If the other problems with this particular data set (blurring, mosaicking) had not arisen, it was my intention to investigate contextual and texture-based per-field classifiers to perform the automated classification. The potential power of this approach remains untested, but is recommended for future work in preference to per-pixels classifiers. A further alternative route would involve accepting the many small polygons as real and then using a more powerful GIS (e.g. ArcInfo) to aggregate the sub-classes into mappable units. This approach could perhaps have been used with the MEIS data discussed here, but ArcInfo was not available at Southampton at the time this part of the work was being done.

In summary, many of the problems encountered in this study reflected the immaturity of the technology used in the sensing system and in the analysis system, however, there are a small number of important problems which persist, and which relate to the nature of the problem, rather than the way it is represented. These include the spatial heterogeneity of the coastal zone and the sub-pixel mixing which this causes, and the high degree of redundancy in digital multispectral scanner data of such high spatial resolution. These issues will remain even with the very high spatial resolution satellite data which are likely to be used to map the coastal zone in the future, and the work done in this thesis will have lasting value in that it shows one way to overcome these problems.

CHAPTER 6

6. ENVIRONMENTAL MANAGEMENT OF THE ARABIAN GULF COASTAL ZONE

6.1 INTRODUCTION

As discussed earlier in Chapter 4, the physical characteristics of the Arabian Gulf of (a nearly landlocked sea with average depth of 35 metres, slow rate of exchange of water through the narrow Strait of Hormuz, temperature ranging between 35° and 15°, high salinity, and fluctuating nutrient levels) make the Arabian Gulf environment for marine life very stressful and especially vulnerable to damage from oil spills, dispersants and other pollutants. Despite all these conditions, the Gulf's marine and coastal habitats have exhibited, through recent studies, a much richer marine fauna than normally assumed. However, oil spills have been characterised as the environmental disaster of the Century and the Arabian Gulf contains the world's largest offshore oil deposits and production, therefore, the region has become one of the world's busiest oil transport arteries, thus making the environmental degradation deriving from oil pollution in the Gulf is inevitable. Examples from previous oil pollution incidents in the Gulf are discussed in details in Chapter 4.

In addition, and also because of the oil industry, the Gulf region states became among the fastest developing nations in the world. The development has become concentrated along its coast where landfill, dredging and reclamation activities have been conducted systematically on a large scale. MEPA (Saudi Arabia's Meteorology and Environmental Protection Administration) (1982) reported that the degradation of marine environment in the Gulf has been brought about not so much by oil pollution but by the desire to extend the desert seawards for land speculation. Unfortunately the areas chosen for these activities to happen are very high in biological productivity.

In other words, the Gulf has become the focus for intense pressure on the marine and coastal environments, and thus demands effective environmental management. Oil spill and the remote sensing of oil pollution are one significant strand in a complex overall challenge.

Coral reefs with their associated islands, seagrass beds, mangroves, and intertidal salt marshes are the most critical habitats in the Gulf. Biologically they are the most productive habitats in the region. They supply the energy needed to sustain the marine life in the Gulf and provide breeding sites for many endangered animal marine species such as the green turtle and the hawksbill turtle (MEPA, 1982; Al-Amirah, 1985).

It is time now to consider preservation of these habitats in the Gulf more seriously. Environmental management is clearly needed for the protection of the marine and coastal renewable resources in the Arabian Gulf. However, managing the genuine complexities inherent in natural systems requires an interdisciplinary approach rather than sectoral. It requires understanding of the system complexity and behaviour in order to determine the future needs and responses (Sheppard *et al.*, 1992). Clark (1986), in addition, discussed how conflict is so common in this context and he stated that:

"The notion of conflict is familiar in ... the management literature in general,....Now, in itself conflict is not inherently destructive. It performs for environmental management a role very similar to that played by competition in a free-market economy. It can be harnessed to positive ends - controlling the excesses of unconstrained economic development, whilst simultaneously blunting the extremes of environmental bigotry. But this cosy idea of balance and compromise can certainly not be taken for granted : it is achieved, if at all, only through a convergence of thinking about what development is reasonable in a particular environmental context - and this in turn is closely connected to the establishment of unambiguous communication between the interest groups involved."

(Clark, 1986).

In order for coastal environmental management to proceed, it requires as a first step detail survey of the coastal zone to identify the distribution and use of coastal resources. Which resources are more vulnerable to environmental pressures and damage and establishment of protected areas? This is can only be accomplished by sensitivity assessment and mapping , which is being increasingly used around the world for coastal zone management. Sensitivity mapping provides a technique to assist response coordinators and government agencies in planning strategies for protection.

In this chapter I will discuss the establishment of environmental sensitivity mapping for oil spill response planning in the coastal zone of northern Qatar, the Arabian Gulf. No such system exists for Qatar, this present attempt is considered to be the first one. Remote sensing and GIS technologies are used, in addition, for enhancing the sensitivity mapping system. Digital and visual image processing techniques are applied to the remotely sensed data for more accurate identification of oil-sensitive shoreline. All the information captured for the coastal zone (such as: oil-sensitive shoreline, oil-sensitive wildlife, access, and protection information) are placed in a GIS database for further manipulation and rapid access and query. Details of the image processing techniques applied to the remotely sensed data are discussed in Chapter 5, and details of building a GIS database and producing a coastal information system for oil spill response planning in northern Qatar are discussed in Chapter 7.

In addition, it is also necessary to define and understand the concept of environmental assessment (EA) as one part of the whole environmental management system. National and regional initiatives of coastal management in the Gulf will be discussed, plus the impact of other environmental pressures than oil spill. Details of the impact of oil spills in the Gulf are discussed in Chapter 4.

6.2 ENVIRONMENTAL ASSESSMENT

Marine and coastal environments throughout the world and over the past century have became subject to increasing human pressures, most of which appear to have resulted in harmful environmental effects. This is illustrated in the diagram by HALCROW (1995) in Figure 6.1, and is described by Clark (1992) who has defined the maritime pollution as:

> "...the introduction by man, directly or indirectly, of substances or energy to the marine environment resulting in deleterious effects such as harm to living resources; hazards to human health; hindrance of marine activities including fishing; impairment of the quality for use of seawater; and reduction of amenities."
>
> (Clark, 1992).

There is a strong increase in demand among the nations to assess the environmental impact of human activity on the natural environment, and environmental assessment is a technique that is being increasingly used for this purpose. Environmental assessment was first introduced in the National Environmental Policy Act (NEPA) by the United States of America in 1969 (Shears, 1990). Due to this recent origin, fast worldwide use, interdisciplinary nature, and the loosely definition of the associated terminology, considerable confusion has resulted (Shears, 1990). Therefore, environmental assessment and its associated terminology have been defined as follows:

1) Environmental assessment (EA):
Is a procedure which aims to provide the information needed to determine whether a project is environmentally acceptable, where it should be located, how it should be designed, operated and its waste disposed of, and what should be done with the site on shutdown and decommissioning to restore or enhance environmental quality.

2) Impact assessment (IA):
Is that part of the environmental assessment process which predicts the environmental impact of a project on specific components of the environment and evaluates the significance of any adverse effects.

3) Environmental statement (ES):

Is a document describing the matters considered during the environmental assessment procedure.

The overall aim of EA is to assess and predict the likely environmental impact of a project at an early stage in the development process, and to suggest means to minimize or prevent any adverse effects.

(Shears, 1990).

6.3 ENVIRONMENTAL PRESSURES AND EFFECTS IN THE GULF OTHER THAN OIL

The impact of oil pollution on the marine and coastal ecology of the Gulf has been discussed in Chapter 4. However, the Gulf's marine and coastal ecology have suffered from other environmental pressures caused by the human uses of these environments. The human uses of coastal zone and offshore areas in the Gulf have increased dramatically over the recent years and more heavy uses are likely to continue in the future. This is not the focus of the present study, but a considerable amount of environmental degradation has resulted from the human uses which have unexpected effects. Discussion of some of these effects, therefore, is essential and will uphold the importance and necessity of the environmental sensitivity mapping for the coastal zone in the Gulf.

Environmental sensitivity mapping is a technique that can be used not only for oil spill response planning, but also for the establishment of a coastal zone management programme or plan. Sheppard *et al.* (1992) has summarised in Table 6.1 the coastal and marine uses and major environmental pressures in the Arabian region, including the Red Sea, Gulf of Aden, Arabian Sea, Gulf of Oman and the Arabian Gulf.

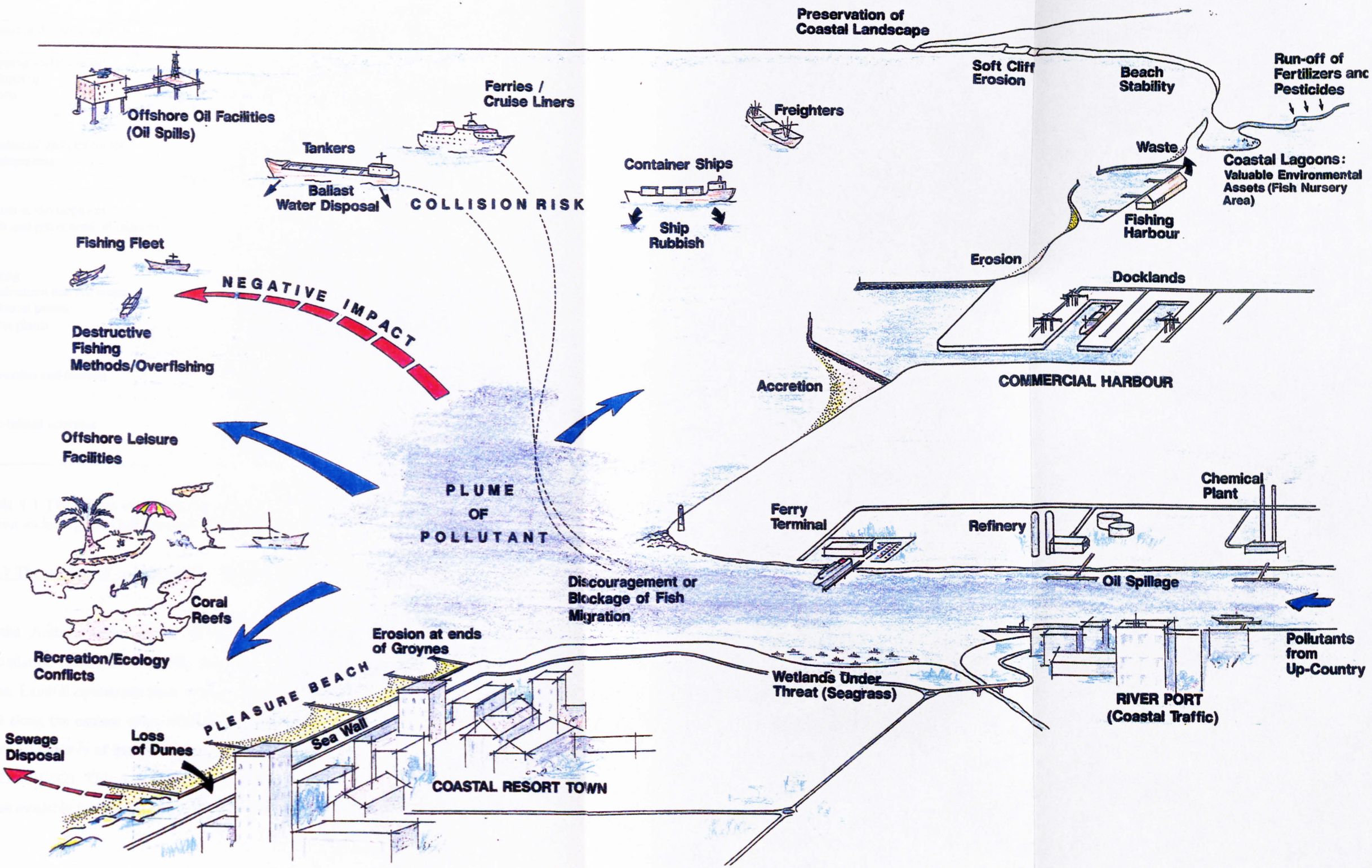


Figure 6.1 Problem of the coastal zone (Source: HALCROW, 1995).

Coastal and marine uses	Actual or potential environmental pressures
Shipping and transport	
Shipping	Oil spills; anchor damage
Ports	Coastal reclamation and habitat loss; dredging, sedimentation; oil and other pollution
Residential and commercial developments	Coastal reclamation and habitat loss; dredging, sedimentation; sewage, fertilizer and other effluents; eutrophication; solid waste disposal
Industrial development	
Oil and petrochemical industry	Oil, refinery and other effluents containing heavy metals; drilling muds and tailings; air pollution
Mining	Sedimentation and elevated heavy metal levels
Desalination and sea water treatment plants	Effluents with elevated temperatures, salinities and sometimes heavy metals and other chemicals
Power plants	Various effluents; air pollution, increasing green-house gases and global warming; acid deposition
Recreation and tourism	Decline in "curio" species; reef degradation; anchor damage; eutrophication (e.g. from resorts and hotels)
War-related activities	Multiple pressures and ecological effects (direct marine and atmospheric)

Table 6.1 The effects of human use of the coastal and marine environments of the Arabian region including the Gulf (Source: Sheppard *et al.*, 1992).

6.3.1 The impacts of coastal landfill, dredging, reclamation and sensitive habitats loss

In the Arabian Gulf besides oil pollution, a considerable amount of environmental degradation results from landfill, dredging and reclamation operations in the coastal zone areas. Landfill operations have been conducted on a large scale over mangroves and tidal flats along the eastern coast of Saudi Arabia. For example seven trucks had been seen for every 10 minutes of the working day dumping rock and sand over these sensitive habitats (MEPA, 1982). This is done for unnecessary coastal development while there is so much space available further inland for housing and construction purposes (MEPA, 1982).

Dredging and reclamation, in addition, are two harmful operations that often occur simultaneously in the shallow coastal waters. Dredging usually supplies the infill sediment material required for coastal reclamation activity. The purpose of these two activities is usually for the construction of new residential areas, causeways, ports, jetties, corniche roads and other engineering works (Sheppard *et al.*, 1992). The Arabian Gulf has become the place for more of these activities on very large scale. The areas chosen for these activities happen to be on very sensitive and biologically productive environments.

The causeway between Saudi Arabia and Bahrain is consider the world largest offshore construction, which is crossing 25 kilometres of shallow sea of an average 5 metres depth. It passes 28.5 metres above the water (Figure 6.2) and is able to carry 3000 vehicles per hour (Vousden and Price, 1985). Although the causeway was designed to have the least damage to the marine environment, nevertheless, heavy dredging and coastal reclamation were involved. About 60 million m^3 of marine mud and sand were dredged from 15-20 km^2 of shallow coastal waters and habitats near Bahrain (Linden *et al.*, 1990).

Dredging has also taking place in the modern city of Jubail, eastern coast of Saudi Arabia, to provide the land fill material needed for the new development of residential and industrial areas. Approximately 46.5 km^2 of coastal habitats have been dredged and more than 200 million m^3 of sediments adjacent to the development site were removed (IUCN, 1987). Now approximately 40% of the eastern coast of Saudi Arabia has been developed by using extensive infilling and reclamation and about only 4 km^2 of mangroves remain along this coast (IUCN, 1987; Sheppard and Price, 1991; Price *et al.*, 1987).

Similar activities have occurred in almost most of the Gulf's countries such as Kuwait, Bahrain, Qatar, and The UAE. In Bahrain for example more than 30 km^2 is now reclaimed land (Madany *et al.*, 1987) which is involved in the loss of the original intertidal ecosystems. In addition, there is a future plan in Bahrain for infilling an area of 200 km^2 (Linden *et al.*, 1990).

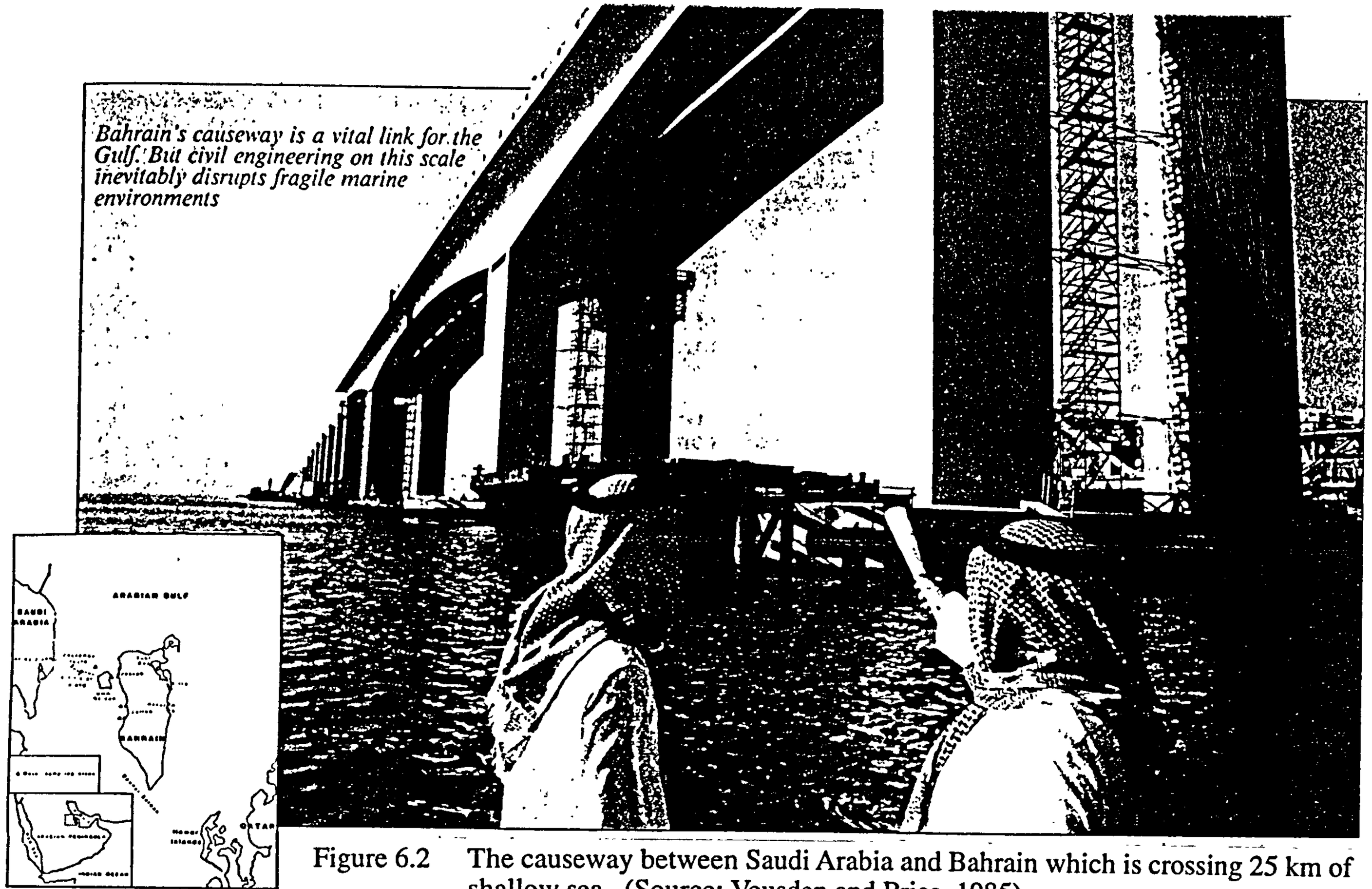


Figure 6.2 The causeway between Saudi Arabia and Bahrain which is crossing 25 km of shallow sea (Source: Vousden and Price, 1985).

In Qatar dredging and reclamation activities were carried out in the shallow coastal water north of Doha City, eastern coast of Qatar (Figure 6.3). The purpose was for coastal development such as residential areas, corniche roads and other constructions of modern Doha City. At present and just north of this reclaimed area dredging is occurring in the coastal beach deposits and sabkhah for the purpose of the development of new and modern shore residences. This project is called the West Bay Lagoon (Figure 6.3). Beside the direct and permanent loss of habitat, landfill, dredging and reclamation activities increase sedimentation (Sheppard *et al.*, 1992), which will smother habitats and limit the photosynthesis of communities like coral reefs, seagrasses and algal mats (Vousden and Price, 1985; IUCN/UNEP, 1985; IUCN, 1987; Ormond, 1987)

The eastern and northeastern coastal zones of Qatar happen to be more developed than the western side. Many shore residences and jetties are scattered over the coast, some of which are located in or very near to sensitive areas such as mangroves, salt marshes and intertidal zones. Jetties have been seen stretching out from the shoreline crossing the sensitive intertidal zone and shallow water to reach for the deeper water areas (see Chapter 5: Figures 5.30 and 5.31).

The northeastern shoulder of Qatar peninsula, in addition, comprises two big embayments, Al-Khawr and Al-Dhakhirah, where large stands of mangroves, salt marshes and wide intertidal areas are colonised (see Chapter 3 for more information on the coastal environmental geology and geomorphology of this area). In order for this area of Qatar to conserve its ecological integrity, it is important that no development take place in this area and human activity should be reduced to a minimum. In other words, the northeastern shoulder of Qatar peninsula should be established as a national park, where access and activities can be controlled. This is should be in fact apply not only to the northeastern of Qatar but also to many sensitive coastal areas and offshore islands in the Arabian Gulf. Such issues lie at the heart of sensitivity assessment.

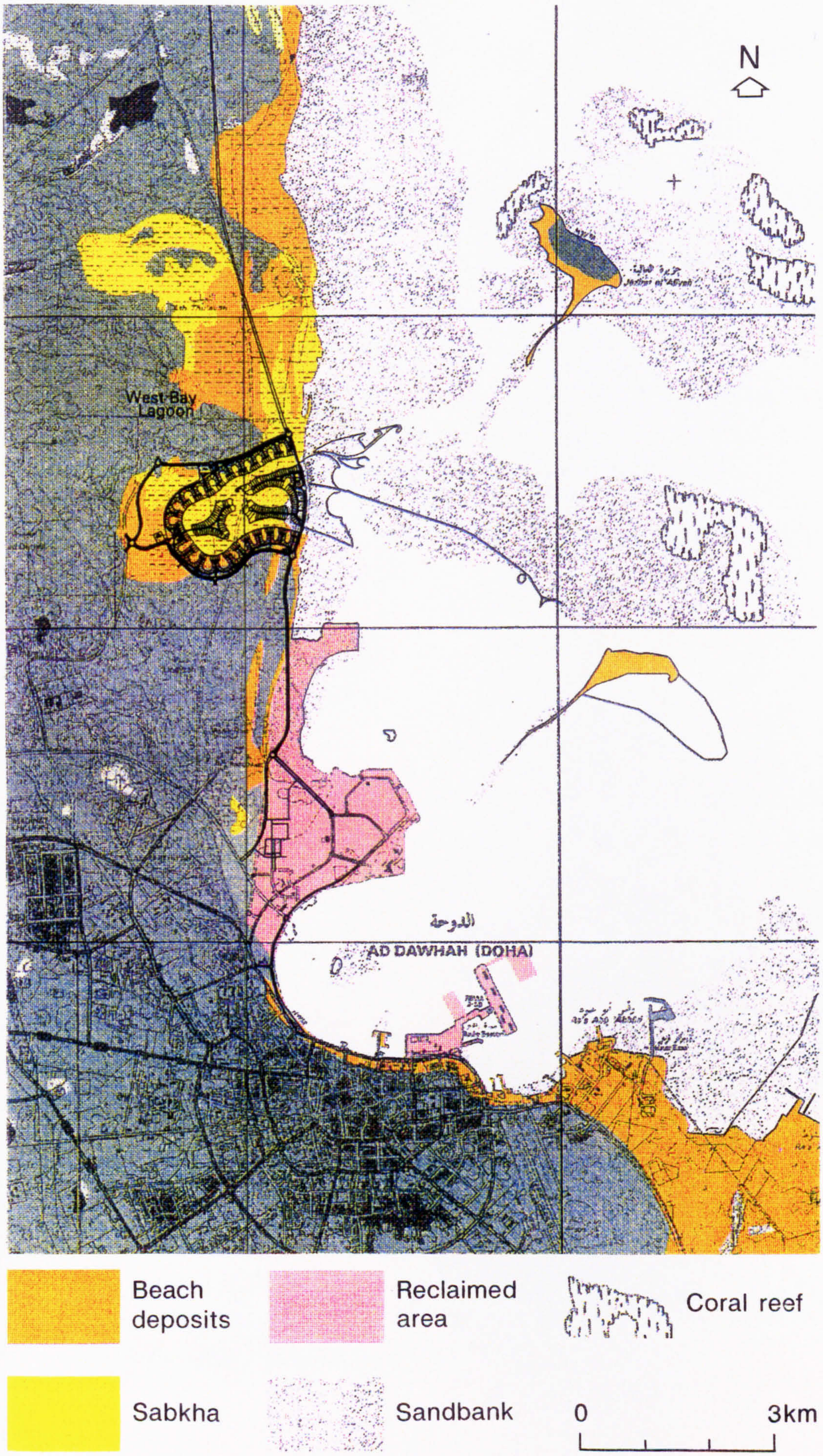


Figure 6.3 Reclamation activities carried out in the shallow coastal water north of Doha City (Source: HALCROW, 1995).

However, there are two cities named Al-Khawr and Al-Dhakhirah located very near to the mangroves, salt marshes and sabkhahs in the northeastern shoulder of Qatar peninsula. The growth of these cities plus the growth of shore residences, jetties and roads crossing sabkhah areas will increase the environmental pressures on these very sensitive and biologically productive environments (see Chapter 5: Figures 5.30 and 5.31).

Environmentally, coastal zone landfill, dredging and reclamation are extremely damaging activities, so why do they occur systematically over the sensitive parts of the coastal zone areas while so much space further inland? The answer to this question could be the lack of scientific knowledge and thinking that these coastal shallow water habitats are "worthless swamps" (MEPA, 1982). In addition, there is the economic attractiveness of coastal sites for land speculation. A major awareness dissemination programme is needed.

The coastal zone shallow water habitats of the Arabian Gulf (which include seagrass, intertidal zone, mangrove, salt marsh, algal mat, and sabkhah) are in fact extremely productive biologically. They support a dense population of invertebrates and form the nutritional basis on which the Arabian Gulf ecosystem depends (MEPA, 1982). Moreover, they provide the "international airports" for many migratory seabirds and marine animals. Any environmental degradation for these habitats in any country of the Arabian Gulf will result in the decline of commercial fisheries in the whole Gulf. In addition it will also further reduce the survival of many endangered animal species including those of global significance. For these reasons we have treated the sections of this chapter as a regional environmental management problem rather than a single coastal country environmental management problem. We believe that the need for international environmental management agreements between the Gulf's countries is important as stated by Vousden and Price (1985), and Sheppard *et al.* (1992):

> "Most important, more and more people realise that the Gulf, as an almost enclosed waterway with resources that cross national boundaries needs to be managed and conserved by a joint venture between all the Gulf countries."
>
> (Vousden and Price, 1985).

"Upholding regional and international agreements is particularly important in seas like the Red Sea and Gulf, whose trans-boundary resources constitute a "global commons" shared by many countries."

(Sheppard *et al.*, 1992).

6.3.2 The impacts of human predation and the lack of the scientific knowledge

Human predation of marine wildlife and eggs is a practice that taking place throughout the Arabian Gulf region. In Qatar for example, egg collection of the seabird *Socotra cormorant* takes place on many offshore islands and rocks where this seabird is known to breed. Its nest is a scrape on the ground and its main food is fish. The egg collections are usually made by the fishermen and people live in small town and villages along the coast. In addition, collecting turtles and their eggs is also a common practice taking place on the mainland coast and offshore islands. Many people in the Gulf are used to eating turtle's meat. Therefore, human predation of marine wildlife and eggs may be an important cause limiting their population in the Gulf region (Sheppard *et al.*, 1992).

The same practices have been seen throughout the Gulf region. Bird eggs are also taken and sold by the fishermen from coral islands offshore the Saudi coast (IUCN, 1987). A minimum of 1000 Green turtles are taken annually by the people from nearby feeding pastures on Masirah Island offshore the Omani coast (Ross and Barwani, 1979; Sheppard *et al.*, 1992). This may be due to the lack of the scientific knowledge of the fishermen and people in the Gulf, that these marine wildlife are endangered species and they must be protected.

Therefore, the development of a comprehensive public awareness programme in the Gulf region by using posters, audiovisuals and other materials, is very essential to reduce and stop the collection of marine wildlife and eggs. In addition, there is a real need for environmental wildlife laws and regulations in the Gulf region for protecting the marine wildlife. Which will requires a basis of formal sensitivity assessment and mapping.

For the first time in Qatar, during August 1996 a large number of fish plus turtles and other marine wildlife were found dead along the Qatari coast as reported by ALWATAN news paper published in Qatar dated 27 August and 1 September, 1996. The Environment Department in Qatar explained that the cause of this incident could be related to the high increase in the weather temperature for this summer. Few days later an oil spill was reported by the local people in the east coast of the country. The spill was about 3 km long and 0.2 km wide and located in the southeastern waters of Qatar, not far from the mainland. The Environment Department then suggested that the cause for the death of the marine wildlife maybe more related to this recent oil spill rather than the increase in the temperature. However, the cause still remains unknown. Indeed, the establishment of marine and coastal research and monitoring programmes relating to all types of pollution is needed for Qatar and the Gulf region as a whole.

6.4 BACKGROUND-MANAGEMENT INITIATIVE IN THE ARABIAN GULF

An integrated approach rather than the usual sectoral approach to research and management has been selected by two countries in the Arabian Gulf, Saudi Arabia and Oman as discussed by MEPA, 1982; Salm and Dobbin, 1987; and Sheppard *et al.*, 1992. In the 1980s the Meteorology and Environmental Protection Administration (MEPA) of Saudi Arabia carried out an assessment of natural resources of Saudi Arabia coasts as part of planning for the region. The main goal was the development of a national coastal zone management programme, which aims to provide a structure for balancing the needs of development with those of conservation. Many important tasks were identified from the proposed coastal zone management programme.

Despite the fact that this programme has not yet been implemented as a whole, many of the tasks recognised are now developed such as the mapping of important and critical habitats and the determination of areas in urgent need for conservation (Sheppard *et al.*, 1992). However, environmental degradation and loss of mangroves, for instance, is still occurring in some coastal areas of Saudi Arabia. Therefore, real management is indeed needed to keep pace with the human demands placed on the marine environment.

The coastal zone management plan of Oman which commenced in the beginning of the 1980s and is still under development is considered a particularly successful example in the Arabian region (Salm and Dobbin, 1987; Sheppard *et al.*, 1992). Many aspects of this management plan can be used as a useful case study and applied elsewhere in the Arabian Gulf. The structure of the coastal zone management plan contains three action components (Salm and Dobbin, 1987; Sheppard *et al.*, 1992) : 1) establishment of general planning policies to provide a broad-brush development guidance in the coastal zone and hopefully avert the emergence of new conflicts; 2) establishment of protected areas to enable intensive management of specific sites of particular value; and 3) identification of specific remedial actions for the numerous management issues in the coastal zone and assign these to a responsible agency.

The goal of the plan, in addition, is to establish a new institutional structure for coastal zone management in Oman. The relevant parts of coastal zone management have been delegated to each ministry within the framework of overall national policies and objectives. This is to enable load sharing rather than an all-or-nothing approach to the coastal zone management problem (Salm and Dobbin, 1987). Marine conservation and management, in addition, has been more progressive in Iran, although little information available in the literature (Sheppard *et al.*, 1992).

After the launch of the Regional Seas Programme by UNEP (United Nations Environment Programme) in 1974 which includes 11 regions and more than 120 coastal states, a regional programme was adopted in 1978 for the Gulf region. This programme is called the Kuwait Action Plan (KAP) which came out from the common interest of the Gulf States (Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia and United Arab Emirates) in protecting from pollution the marine area of their region (UNEP, 1983).

KAP forms part of the broader Kuwait Regional Convention on the Protection of the Marine Environment from Pollution, and all the Gulf states are signatories to the convention (Sheppard *et al.*, 1992). KAP works through close cooperation with international, regional (such as ROPME = Regional Organization for the Protection of the Marine Environment) and national organisations. Many of the major conservation and research initiatives in the Arabian Gulf have been part of the Regional Seas Programme of UNEP.

6.5 ESI MAPPING: A BACKGROUND

ESI mapping is commonly associated with oil spill response and contingency planning. ESI has proved to be a useful technique for the identification of the environmentally sensitive areas, set priority of protection and the type of oil spill combating action likely to be effective for each area (ROPME, 1990). ESI, in addition, is a classification and ranking of the relative sensitivities of various geomorphic coastal environment types on a scale of 1 to 10 in terms of indicating the persistence of oil and potential for biological habitat damage. In cartographic form, coastal types are colour coded according to rank to allow rapid identification of differences.

The most highly sensitive coastal types would have the highest priority for protection and are colour coded in bright red. While low sensitive coastal types would have low priority for protection and are colour coded in black. Therefore, ESI provides a tool to assist spill-response coordinators and government agencies in planning strategies for protection (Gundlach and Hayes, 1978; Hayes *et al.*, 1980; Pavia *et al.*, 1982; Jensen *et al.*, 1990; Narumalani *et al.*, 1992).

Oil spill ESI has been developed over time. The concept was first introduced in 1976 by Hayes *et al.* during the field investigation of massive oil spills in the United States. The first application of the concept was called the oil spill susceptibility index which was used during the geological sensitivity mapping of the coastline of Alaska. The index incorporated measures of coastal form and sediment which influenced the main diagnostic attribute (Clark, 1986). Moreover, it was based on the physical persistence or longevity of oil in each environment in the absence of cleanup operations.

Two years later the concept was expanded by Gundlach and Hayes (1978) to include some biological considerations (Table 6.2). The terminology, in addition, was changed to oil spill vulnerability index. The oil spill vulnerability index was based on three diagnostic attributes as discussed by Clark (1986): 1) shoreline interaction with the oil; 2) oil persistence in that environment; 3) the extent of biological damage. In 1980 Hayes *et al.* decided to develop their concept further to integrate more biological features into the index. Their main focus was more on the migration of marine mammals and birds. For example, this indicated areas critical to these species for reproduction, feeding, and the seasons in which these species use certain areas (Hayes *et al.*, 1980). Therefore, the terminology had again altered and now is called the Environmental Sensitivity Index.

So the ultimate goal of the ESI mapping is to generate maps of coastal environmental sensitivity with respect to oil spill impact (Hayes *et al.*, 1980). These maps will provide the necessary information and assistance to oil spill coordinators in planning strategies for protection. Usually four types of information are included in the ESI maps (Jensen *et al.*, 1990; Narumalani *et al.*, 1992): 1) planimetric basemap; 2) shoreline sensitivity index; 3) information on oil-sensitive wildlife; and 4) access and protection features.

The traditional ESI mapping techniques (Hayes *et al.*, 1980; Jensen *et al.*, 1990) are involved in the use of existing topographic charts as planimetric basemaps. Shoreline characteristics are mapped by aerial reconnaissance of the site flown at low tide and by field work. Information on the distribution of wildlife sensitivity is collected from field study and identified by symbols on the map which are designed to assess rapid response actions. Access and protection features such as marinas, important recreation beaches , and desalination and power plants are also depicted by symbols on the map.

The sensitivity scale is maybe regionally-specific because the sensitivity of the coastal zone and the environmental condition vary between regions. Some similarities between the different sensitivity scales are common because the coastal zone types and conditions are sometimes cross regions. The standard vulnerability index in Table 6.2 is developed specifically for the coastline of the southeast coast of the United States. In the present research we are going to develop the prototype ESI mapping for the coastal zone of northern Qatar by using remote sensing and GIS technologies.

Vulnerability Index	Shoreline Type	Comments
1	Exposed rocky head-land	Wave reflection keeps most of the oil offshore. No cleanup is necessary.
2	Eroding wave-cut platforms	Wave swept. Most oil removed by natural processes within weeks.
3	Fine-grained sand beaches	Oil doesn't penetrate into the sediment, facilitating mechanical removal if necessary. Otherwise, oil may persist several months.
4	Coarse-grained sand beaches	Oil may sink and/or be buried rapidly making cleanup difficult. Under moderate to high energy conditions, oil will be removed naturally within months from most of the beachface.
5	Exposed, compacted tidal flats	Most oil will not adhere to, nor penetrate into, the compacted tidal flat. Cleanup is usually unnecessary.
6	Mixed sand and gravel beaches	Oil may undergo rapid penetration and burial. Under moderate to low energy condition, oil may persist for years.
7	Gravel beaches	Same as above. Cleanup should concentrate on the high-tide swash area. A solid asphalt pavement may form under heavy oil accumulations.
8	Sheltered rocky coasts	Areas of reduced wave action. Oil may persist for many years. Cleanup is not recommended unless oil concentration is very heavy.
9	Sheltered tidal flats	Areas of great biological activity and low wave energy. Oil may persist for years. Cleanup in not recommended unless oil accumulation is very heavy. These areas should receive priority protection by using booms or sorbent materials.
10	Salt marshes and mangroves	Most productive of aquatic environments. Oil may persist for years. Cleaning of salt marshes by burning or cutting should be undertaken only if heavily oiled. Mangroves should not be altered. Protection of these environments by booms or sorbent material should receive first priority.

Table 6.2 Shoreline environmental classification in order of increasing vulnerability to oil spill damage (Source: Gundlach and Hayes, 1978).

In 1990 the concept of ESI mapping was enhanced more by applying remote sensing and GIS technologies. Jensen *et al.* (1990) demonstrated the advantages of using SPOT imagery for Marco Island area, southwest Florida to produce an up to date and accurate planimetric basemap in order to overcome the problem of lack of adequate planimetric basemap for many areas of the world. Information for shoreline ESI can be interpreted from SPOT imagery by using visual and digital image processing techniques.

The traditional method of mapping the coastal features planimetrically by viewing the terrain obliquely is very difficult especially in complex coastal zones and can introduce some errors in the final maps. Remote sensing can provide detailed, accurate and up to date information through the analysis of the satellite imagery (Jensen *et al.*, 1990; Jensen *et al.*, 1992; Narumalani *et al.*, 1992). By placing all the information extracted from the remotely-sensed data plus the information about oil-sensitive wildlife, access and protection in a GIS, rapid retrieval and querying can be achieved (Jensen *et al.*, 1990; Grice, 1991; Jensen *et al.*, 1992; Narumalani *et al.*, 1992; Roper, 1993; Clark, 1994; Collier *et al.*, 1995; Khamis *et al.*, 1995).

In the Arabian Gulf Landsat TM imagery was used for the coastal zone environmental sensitivity mapping (Jensen *et al.*, 1992; Narumalani *et al.*, 1992; Narumalani *et al.*, 1993). The coarse spatial resolution of the satellite sensors, however, tends to generate many mixed pixels in the image of mixed land cover types especially in coastal zones where convoluted and complex environments are present. Coastal zones would require very high spatial resolution remote sensing sensors for detailed mapping of their convoluted and complex environments (see Chapter 5). Many of the future satellite programmes are tending toward the very high spatial resolution sensors to fill the needs of high spatial resolution satellite data.

At present high spatial resolution airborne remotely sensed data can be used to produce very detailed coastal zones environmental sensitivity maps especially in areas like Qatar where full recent coverage of high spatial resolution airborne data exist for the whole coastal zone. However, handling and using such large volumes of high spatial resolution data (2m) for large coastal zone area is very difficult. Chapter 5 discussed the handling and use of high spatial resolution data for coastal zone environmental sensitivity mapping for the first time in Qatar.

6.6 DEVELOPMENT OF THE ESI MAPPING FOR NORTHERN QATAR COASTAL ZONE USING HIGH SPATIAL RESOLUTION AIRBORNE MEIS DATA & CONVENTIONAL SURVEYS

Qatar is amongst those countries surrounding the Arabian Gulf that has no ESI mapping for its coastal zone environment, though the Arabian Gulf is known to be among the most polluted seas in the world from oil pollution (see Chapter 4). Qatar, in addition, occupies a peninsula projecting due north from the Arabian shore into the Gulf, and this situation makes the northern half of Qatar vulnerable to any oil spills that might occur in the Gulf (see Chapter 3).

Aboul Dahab (1994) and Aboul Dahab and Al-Madfa (1992) describe the distribution of oil pollution along the Qatari coastline, which is characterised by significant variation in level. This level varies from the heavily polluted northern and northwestern shores to pollution free shores in the southeast. This can be attributed firstly to the location of the Qatar peninsula, and secondly to the meteorological and hydrological conditions in the Arabian Gulf region.

After the discussion in Chapter 4 about the impact of oil spills on the marine and coastal environments of the Gulf and the discussion in the first half of this chapter about the importance of the coastal zone management for the preservation of the Gulf habitats, today still there is no strategy in Qatar to consider in such events for the planning purposes and the prompt action necessary for cleanup operations with minimal impact on the environment.

Oil spills will continue to occur in the Arabian Gulf and northern Qatar will always be vulnerable to oil pollution and access to information like: the location of the spill, potential area of impact, the environmental sensitivity of the impact area, and the available resources to combat the spills are very important for personnel in charge of cleanup operations in order to achieve the aim of decreasing impacts associated with the oil spills.

In Qatar none of this information is available for personnel in charge of cleanup operations, therefore, creating ESI mapping for northern Qatar is a prime achievement. It will reflect the diverse environments and marine habitats that are present in northern Qatar and which respond differently to environmental pressures such as oil spills. Some of these diverse habitats are more vulnerable to damage than others.

Therefore, the creation of the ESI will provide a system that can be used for rapid evaluation of the impact of oil spills and the planning for effective spill response in Qatar. It will provide spill-response coordinators in Qatar with an easily accessible summary of key areas needing immediate response and protection. In the next section below, the methodology used for the creation of the ESI for northern Qatar is discussed in more details.

6.6.1 The creation of the ESI for northern Qatar coastal zone

The methodology used to yield the necessary information for the creation of the ESI is based mainly on the analyses of the remotely-sensed data and conventional surveys. The sensitivity classification of the coastal zone is extracted from the high spatial resolution airborne MEIS data, geologic and topographic maps, available literature and field work.

In addition, the ranking of the coastal zone sensitivity types was based on known interaction of oil with various coastal types which have been observed over the past years (Gundlach and Hayes, 1978; Hayes *et al.*, 1980; Pavia *et al.*, 1982; Webb, 1985; Clark, 1986; Jensen *et al.*, 1990; Narumalani *et al.*, 1992; Jensen *et al.*, 1992; Clark, 1994). The most sensitive environmental areas , for example, are salt marsh, mangrove, seagrass and coral rock bed, while the least sensitive areas are manmade seawall, drifted seaweed and drifted wood beach, and rocky headland.

Accurate and up to date topographic and geologic maps exist for Qatar which were produced from the interpretation of aerial photographs and were recently updated by the satellite imagery. These maps show the various coastal geomorphology and composition plus the location of offshore reefs and sand banks. In addition, the maps show the location of the urban areas along the coast, jetties, road network and the desert tracks. Not all coastlines in Qatar are served by roads. Desert tracks must sometimes be used in conjunction with the road network to reach the desired area of the shoreline. The road network is of critical importance when crews must be dispatched to the various shorelines (Jensen *et al.*, 1990).

Topographic maps are used to produce the planimetric basemap for the ESI of northern Qatar while the geologic map of Qatar and field work are used to extract the varied geomorphology and composition of the shorelines plus offshore reefs and sand banks which are needed for the creation of the ESI. Moreover, all the available literature is collected and analysed to add more information to the classification of the ESI, but few sources are available for the coastal zone of Qatar: Owens and Reimer ,1991; Khamis *et al.*, 1990; Khamis *et al.*, 1995; Cavelier, 1970; Fock *et al.*, 1986; Alsheeb, 1988; Shinn, 1973a; Shinn, 1973b; Aboul Dahab, 1994. Existing maps in Qatar are found to be lacking biological information on the shoreline. Therefore, vegetated habitats of the fragile intertidal zone have been classified from the high spatial resolution airborne MEIS imagery to integrate biological features into the ESI classification (see Chapter 5).

Three types of vegetated habitat have been classified in the shallow water and fragile intertidal zone for the first time in Qatar using the airborne MEIS data. These habitats are seagrass beds, salt marshes which are dominated by *Arthrocnemum glaucum* (Halophytes), and scattered mangrove forests. During the field work, the sensitive salt marsh that was mapped in the extreme north of Qatar was found to be a breeding and resting area for a large number of two types of water birds (*Socotra cormorant* and *Kentish plover*) (Khamis *et al.*, 1995).

The seagrass beds which are also mapped in the shallow water of the extreme north of Qatar were found to be a feeding area for the most popular and expensive fish (*Siganus canaliculatus*) in Qatar and the Gulf region (Khamis *et al.*, 1995). In addition, in the quiet water embayments and complicated tidal channel system in the northeastern of Qatar and where the scattered mangrove forests are mapped (Chapter 3), the whole area was found to be colonised by a very large number of crabs.

The high spatial resolution airborne MEIS data have allowed the seagrass beds in the coastal zone of Qatar to be mapped for the first time in clear water (0.75 m deep). The salt marsh in the extreme north of Qatar was missmapped as reef in previous maps, possibly due to the use of black-and-white aerial photographs for the interpretation and generation of these maps. This is because of the similarity in shape and texture of the salt marsh plants and the reefs in the photographs (Khamis *et al.*, 1995).

6.6.2 Developing the proposed ESI for northern Qatar with the local experts

Table 6.3 represents a summary of the proposed ESI classification for northern Qatar as being built from the airborne MEIS data and the conventional surveys in Qatar. In order to perform the comparison between the proposed ESI and the local experts, a questionnaire about the coastal zone sensitivity classification of northern Qatar was designed using Table 6.3 and sent to local experts in Qatar to elicit opinions on the ESI ranking of the various coastal zone types.

The questionnaire results comprise of four columns titled: 1) Coastal zone type in Qatar, 2) Vulnerable to oil, 3) Sensitive to oil and 4) Cleanup. In the column titled Coastal zone type in Qatar, all the classified coastal zone types in northern Qatar using the airborne MEIS data and the conventional surveys were listed. The other three columns were left blank for the response scoring by local experts on a scale of 1 to 10 for each type of the coastal zone. For example, 1 is least vulnerable/sensitive/cleanup and 10 is most vulnerable/sensitive/cleanup.

Vulnerable to oil means that some coastal zone types are very vulnerable to damage from oil spills or cleanup operations. For example, intertidal zones with tidal channels are very vulnerable because oil easily collects in the complex tidal channels and very difficult to remove. Moreover, the muddy sediments of this area are considered to be the place for the most sensitive stages of the life cycle for many marine organisms. Sensitive to oil, in addition, means the same as vulnerable to oil but with more focus on the migration of marine mammals and birds. For example, indicated areas critical to these species for reproduction, feeding, and the seasons in which these species use certain areas. Cleanup means that during an oil spill which part of the coastal zone would receive the highest priority for cleanup operations. This will depends on the vulnerability and the sensitivity ranking of each type of the coastal zone. The highest the scoring is, the highest priority for cleanup activities.

The questionnaire was sent to people that are more involved in the environmental protection in general or at least with the background of the various marine and coastal environments in Qatar that are more sensitive to oil pollution. This is included: 1) Environment Department - Ministry of Municipal Affairs & Agriculture, 2) Environmental Affairs - Qatar General Petroleum Corporation, 3) Marine Science Department - University of Qatar and 4) Scientific and Applied Research Centre - University of Qatar. 18 questionnaires were received and analysed (see Appendix 1) in order to see the level of agreement between the local experts on the proposed ESI for northern Qatar coastal zone. Below is the discussion about the comparison between the proposed ESI and local experts response in the sensitivity ranking of the coastal zone types.

ESI Rank	ESI Coastal Zone Sensitivity Types	Comments
1	Manmade: riprap, rubble and seawall (MEIS data)	Riprap is large bedrock placed systematically in the intertidal zone. Rubble is mixed landfill material placed in the intertidal zone.
2	Flat, dead seaweed and drift wood shores	Drift seaweed and wood may protect the shoreline from being oiled. During the tide oil flushes into the materials and sticks on them.
3	Exposed, cliffed rocky headlands	Wave actions keep most of the oil offshore.
4	Sabkhah: Flat silt/sand supratidal zone	Compacted sediment, tidal or wind-tidal flats that could be oiled during periods of high water level. Oil doesn't penetrate into the sediment.
5	Fine-to-medium grained sand shore zone	Sometimes with well-defined sloping beachface and narrow sand barrier beach ridges. Oil may sink and be buried quickly.
6	Flat, bedrock and/or beachrock shore zone	Sometimes mixed sand and gravel can be found in between. Oil may penetrate between the sand and gravel and solid asphalt pavement may form. In addition, oil will coat the rock beds with thick layer of tar.
7	Sand banks (MEIS data)	More subtidal and offshore and in the water column (high energy area). The sand sticks into the oil which make it heavy so that it can not float on the surface of the water.
8	Flat, compacted mud/silt intertidal zone (MEIS data)	Intertidal area that is high in biological activity. Used by seabirds at low tide and fish at high tide for feeding. Oil doesn't penetrate into the sediment. These areas should receive priority for protection.
9	Sheltered lagoonal tidal flats	High in biological activity and low wave energy. Oil may stay there for a long time. These areas should receive high priority for protection.
= 10	Seagrass beds (MEIS data)	Subtidal areas with very high biological value. This area should receive the highest priority for protection.
= 10	Coral rock beds	More offshore areas with high biological value. These areas should receive the highest priority for protection.
= 10	Sheltered salt marsh and mangrove (MEIS data)	These areas of great biological value and low wave energy. They should have the highest priority for protection. Oil may stay there for years.

Table 6.3 The proposed environmental sensitivity classification for the coastal zone of northern Qatar as extracted from conventional surveys and airborne MEIS data.

Table 6.4 represents the mean response scoring of the sensitivity to oil by the local experts to each individual coastal zone type as extracted from Appendix 1. By comparing the overall scores, the sheltered lagoonal tidal flats; and sheltered salt marsh and mangrove receive almost the same ESI scores as the proposed ESI for northern Qatar coastal zone (Table 6.3). Very good correlation in overall scores appears between the local experts scoring and the proposed ESI for these two types of coastal zone. ESI = 9 was scored by the proposed ESI for the sheltered lagoonal tidal flats and 8.70 by the local experts, and ESI = 10 was scored by the proposed ESI for the sheltered salt marsh and mangrove, and 9.66 by the local experts. Moreover, the level of agreement between respondents is found to be very high for both of these coastal zone types as indicated by the coefficient of variation (Table 6.4).

The seagrass beds, however, received the score of ESI = 8.50 and the coral rock beds the score of ESI = 9.38 by the mean response of local experts. It is not the same scores as indicated by the proposed ESI, but it still falls in the category of high sensitivity to oil pollution. This indicates that the opinion of the average local experts agrees with the proposed ESI for the previous four coastal zone types. Which explains also that the average of the local experts understand the effectiveness of oil spills on these types of sensitive environment.

Some correlation in the overall scores, in addition, can be seen between: Flat, bedrock or beachrock shore zone; fine-to-medium-grained sand shore zone; and sabkhah; compared with the proposed ESI. The rocky shore zone receive the score of ESI = 5.83; the sandy shore zone the score of ESI = 4.94; and sabkhah the score of ESI = 4.33, in the mean response of local experts which are near the proposed ESI scoring. No correlation in the overall scores can be seen between: Manmade, riprap, rubble and seawall; sand banks; exposed, cliffed rocky headlands; flat, compacted mud/silt intertidal zone; and flat, dead seaweed and drifted wood beach, with the proposed ESI. The level of agreement, in addition, between respondents is very low as indicated by the coefficient of variation (Table 6.4).

Coastal zone sensitivity types	The mean response scoring of sensitivity to oil	Variability	
		Stdev	Coeff. of Variation
Manmade, riprap, rubble and seawall	3.61	2.74	75%
Sand banks	3.83	2.97	77%
Exposed, cliffed rocky headlands	3.88	2.13	54%
Subkhah: flat, silt/sand supratidal zone	4.33	2.16	49%
Narrow, sand barrier beach	4.50	1.68	37%
Flat, compacted mud/silt intertidal zone	4.83	1.61	33%
Flat, fine-to-medium-grained sand, shore zone	4.94	1.51	30%
Flat, bedrock or beachrock shore zone	5.83	2.66	45%
Flat, dead seaweed and drifted wood beach	6.16	3.34	54%
Seagrass beds	8.50	1.68	19%
Sheltered lagoonal tidal flats	8.70	1.44	16%
Coral rock beds	9.38	1.03	10%
Sheltered salt marsh and mangrove	9.66	0.59	6%

Table 6.4 Local experts mean response scoring of the sensitivity to oil to each individual coastal zone types in northern Qatar.

Table 6.5, moreover, represent the highest frequency response (mode) of local experts to sensitivity to oil for each individual coastal zone type. By comparing the mode of response in the overall scores, we see very good correlation with more coastal zone types between local experts and the proposed ESI than the comparison of the mean response. Coastal zone types such as: Manmade, riprap, rubble and seawall; narrow, sand barrier beach; fine-to-medium-grained sand shore zone; sheltered salt marsh and mangrove; seagrass beds; and coral rock beds, receive the same ESI scores as the proposed ESI (see Table 6.3 and Table 6.5 for comparison).

In addition, the coastal zone types such as: Sabkhah; flat, compacted mud/silt intertidal shore zone; and sheltered lagoonal tidal flats, receive almost the same ESI scores as the proposed ESI. They only differ with ESI = ± 1 point. No level of agreement can be seen between the mode response of local experts and the proposed ESI for the coastal zone types of: Sand banks; flat, bedrock or beachrock shore zone; exposed, cliff rock headlands; and flat, dead seaweed and drifted wood beach.

Coastal zone sensitivity types	The mode response scoring of sensitivity to oil	Range of response
Manmade, riprap, rubble and seawall	1	1-5
Sand banks	1	1-4
Flat, bedrock or beachrock shore zone	2	1-4
Narrow, sand barrier beach	3	1-4
Subkhah: flat, silt/sand supratidal zone	3	1-6
Exposed, cliffed rock headlands	5	1-6
Flat, fine-to-medium-grained sand shore zone	5	1-7
Flat, compacted mud/silt intertidal shore zone	5	1-4
Flat, dead seaweed and drifted wood beach	10	1-4
Sheltered lagoonal tidal flats	10	1-7
Sheltered salt marsh and mangrove	10	1-13
Seagrass beds	10	1-8
Coral rock beds	10	1-11

Table 6.5 Local experts mode response scoring of the sensitivity to oil to each individual coastal zone types in northern Qatar.

The mode response in Qatar (Table 6.5) is maybe a better representative of the local experts opinion than the mean response, as it appears from the previous comparison results. More correlation can be seen between the mode response (Table 6.5) and the proposed ESI (Table 6.3) than the mean response (Table 6.4). This also may indicates that some people understand the important of the various sensitivities of the coastal zone environment and the effectiveness of oil spills on these sensitive environments. But very few maybe understand the concept behind the Environmental Sensitivity Index.

The technique is excellent in principle but problematic in practice. The design of the questionnaire, in addition, might have some effect on the final scoring response of the local experts to each coastal zone type. Maybe the questionnaire should be written in Arabic language to facilitate the understanding of each coastal zone types and the concept behind the Environmental Sensitivity Index.

In addition, it should be accompanied with explanation booklet about the various coastal zone types and the meaning of vulnerable to oil, sensitive to oil, and cleanup. Examples of international Environmental Sensitivity Index maybe should be included in the booklet. However, oral explanation was made in place for all the people that participated in this study.

In conclusion, the local experts seem to have good understanding about the value of the biological features (such as salt marsh and mangrove) and the impact of oil on these sensitive environments. Therefore, they received a very high rank in their questionnaires. However, they do not have clear understanding about the interaction of oil with every type of coastal environment. They have no clear understanding, in addition, about the wave actions on each type of shore zone. For example, in exposed rocky headlands, the wave actions keep most of the oil offshore and no cleanup is necessary.

Local training is very important and needed in order to have better planning and response for combating the oil spills. This is can be achieved by applying short training courses in oil spills response for the people that are responsible for the protection of the marine and coastal environments in Qatar. Testing the proposed ESI for northern Qatar is also important , and this can be done maybe during the training courses. The creation of the final ESI map of northern Qatar coastal zone is discussed in Chapter 7.

6.6.3 Unit description of the ESI classification

More details of the classification of the ESI which is specifically designed to reflect the coastal zone environments and marine habitats in northern Qatar are discussed below: the classes are arranged from the least sensitive to the most sensitive.

6.6.3.1 Manmade features

This includes riprap, rubble and seawall which are placed by man in the intertidal zone and shoreline. Riprap is large bedrock placed systematically in the compacted intertidal zone (Figure 6.4) in order to trap sediment and fish coming with the tide to feed in this area. This feature is mapped from the airborne MEIS data covering the extreme north of Qatar (see Chapter 5: Figures 5.26 and 5.29). Rubble, moreover, is mixed landfill material placed in the intertidal zone for coastal reclamation.

Oil will interact with each type of these manmade features differently. For example, oil may penetrate into the mixed landfill material, but it may coat the riprap and seawall with thick layer of tar. Cleanup will be difficult for the riprap and rubble, but maybe not for the seawall because oil can be removed by man. If these features are in an area of strong wave actions then no cleanup is necessary because oil will be removed by natural processes.

6.6.3.2 Flat, dead seaweed and drift wood shores

Dead seaweed and drift wood are found covering the shorelines in northwestern Qatar from Ruwais to Al-Zubarah (Chapter 3: figure 3.4) (Aboul Dahab, 1994). This section of the coastal zone is known to be an area of high energy (see Chapter 3: Figure 3.11) where the dead seaweed and various kinds of debris are drifted by the high currents from offshore and deposited on the shores of this area (Figure 6.5). The drifted materials are found covering three shore types: flat sand, flat bedrock and sabkhah (Aboul Dahab, 1994). During an oil spill, the oil will also drift from offshore area by the high currents toward the shallow coastal area. Some oil will be deposited on the shores while large amount of oil will be covering the bottom of the shallow water area. This is what happened during the last oil spills in the Arabian Gulf in January 1991 (see Chapter 5: Figure 5.28 and Chapter 4: Figure 4.4).

Figure 6.4 Example of ESI = 1, riprap is large bedrock placed systematically in the compacted section of the intertidal zone in northern Qatar.

Figure 6.5 Example of ESI = 2, drifted dead seaweed and various kinds of debris covering the shorelines in northwestern Qatar.

From the last oil spills in the Arabian Gulf, Aboul Dahab (1994) describes the entire zone of the northwestern Qatar as a heavily polluted zone. Massive deposits of tarry materials and many kinds of debris are found on the shore zone. Oil is found heavily mixed with the sand in some places, while in other places several layers of oil can be distinguished in the sand which suggests that these shores have been coated by oil several times.

In the places where the drifted materials cover the entire shore, this may protect the shore from being oiled. During the tide oil flushes into the drifted materials and sticks on them (Figure 6.6) which makes the cleanup operation easier since these materials can be lifted manually from the shore. The biological diversity and value of this type of shore is unknown.

This type of coast is not mapped by the geologic and topographic maps of Qatar, but it is described more in the literature that was collected for the coastal zone. In Chapter 3 it was possible to map the zone of high energy from the TM mosaic of band 1. More detailed mapping of which section of the coast that receive much of the drifted materials can be achieved using the high spatial resolution airborne MEIS data.

In addition, airborne MEIS data can be used in the future to produce maps of post-oil spills for the entire coastal zone of Qatar which impacted during the last oil spills in the Arabian Gulf in 1991. This will help to understand the movement of tarry materials around the coasts of Qatar and which part of the coastal zone that is heavily polluted. In Chapter 5 it was possible by using the airborne MEIS data to map the tarry deposits covering the bottom of the shallow water in northern Qatar.

Figure 6.6 Example of ESI = 2, oil flushes into the drifted seaweed and various kinds of debris and stick on them during the high tide in northern Qatar. This is the result from the last oil spills in the Arabian Gulf in January 1991.

Figure 6.7 Example of ESI = 4, sabkhah surface with evaporite crusts in the northeastern Qatar.

6.6.3.3 Exposed, cliffed rocky headlands

Cliffed rocky headlands consist of limestone and dolomitic limestone with no biological value and are more frequently found in the west of Qatar especially around Abruq peninsula (Chapter 3: Figure 3.4). No cleanup operation is necessary for the cliffed rocky headlands because wave actions keep most of the oil offshore or self-clean it rapidly.

6.6.3.4 Sabkhah: Flat silt/sand supratidal zone

Sabkhah deposits are composed of fine silt and calcareous sands, which are widespread along the Qatari coastline. Sabkhah is well mapped by the geologic and topographic maps of Qatar, in addition, sabkhah deposits are characterised in the literature into three categories: 1) subtidal sediment, 2) intertidal sediment and 3) supratidal sediment.

The subtidal sediment occurs in the lagoons or open sea, which are always below the tide and consists of mixtures of pelleted mud and silt-sized carbonate, which appears in predominantly gray colour and contains different amount of winnowed skeletal grains. The biological diversity and value of the subtidal is very high and need to be investigated in more details in the future for the whole coastal zone of Qatar. These subtidal sediments underlay all the intertidal and supratidal sediments.

Intertidal sediments consist of the same sediments as the subtidal zone, but can be distinguished by their light tan colour and many iron-stained root tubes and small holes (Figure 6.11). In the northeastern of Qatar the intertidal sediments are colonised by salt marsh and mangrove frost. The supratidal flats (sabkhah) are interfaced landward by Tertiary outcrops and seaward by the intertidal zones. In many parts of the sabkhah surface, evaporite crusts are occurred (Figure 6.7). More fixed pellet-rich muds and lags of skeletal sand are found in the sabkhah sediments than of the intertidal sediments.

The biological diversity and value of the sabkhah is maybe low, but it needs to be investigated in more details in the future. Sabkhah sediments are more compacted than the intertidal sediments and that will not be oiled unless there is very high water level which could happen only during periods of strong storm. However, self-cleansing is rare and cleanup operations can be damaging.

6.6.3.5 Fine-to-medium grained sand shore zone

Marine calcareous sands of varied extent, principally are localised along the present coastlines and narrow intertidal zones. Also they occur at the edge or within the sabkhah and outline areas previously covered by the Quaternary sea. In the northeastern of Qatar, they also form a thin layer which lies on the rocks beneath. This feature is very well mapped in the geologic map of Qatar which has been used to extract this feature for the environmental sensitivity classification of northern Qatar. Oil may sink and be buried quickly only along the present coastlines and intertidal zones (Figure 6.8) where the sands have direct contact with the sea water. Cleanup operation is very difficult, oil will be removed from the beachface naturally under the energy conditions but only relatively slowly. The biological diversity and value of the sandy shore zone are unknown. Sometimes these sands form narrow barrier beaches with hook-shaped spits at their southern ends and also well-defined sloping beachface. These barrier beaches add protection to the embayments left behind.

6.6.3.6 Flat, bedrock and/or beachrock shore zone

Bedrock and beachrock form small areas which are scattered along the coastlines (Figure 6.9). These features are mapped from the geologic map for the present sensitivity mapping. Usually sand and gravel are found between and around the rock beds. Oil may penetrate between the sand and gravel and solid asphalt pavement may form. Moreover, oil will coat the rock beds with layer of tar. Cleanup operations are very difficult and can be damaging. Oil maybe removed under the energy conditions. The biological diversity and value of this type of the coastal zone are unknown.

Figure 6.8 Example of ESI = 5, calcareous sands localized along the present coastlines and narrow intertidal zones.

Figure 6.9 Example of ESI = 6, oil tar covering the rock beds in the northwestern Qatar during the last oil spills in the Arabian Gulf in January 1991.

6.6.3.7 Sand banks

Sand banks are found more in the subtidal and offshore areas plus in the water column of the high energy area in the northwestern of Qatar (see Chapter 3: Figure 3.11). Sand banks consist of the same sediments of the subtidal zone. Sand banks consist of mixtures of pelleted mud and silt-sized carbonate, which appear in predominantly grey colour and contain different amounts of winnowed skeletal grains.

Sand banks may form in some areas of small and scattered sand bars that are completely buried at high tide. These sand bars are found to be used by seabirds as resting areas (Figure 6.10). During an oil spill the sand tends to stick into the oil which make it heavy so that it can not float on the surface of the water. As a result the oil starts to sink and cover the bottom of the shallow water (see Chapter 5: Figure 5.28). Cleanup is impossible unless the oil is prevented from entering the zones of sand banks, high energy and shallow water. Which can be done by placing booms quickly around these zones soon after the discovery of oil spill.

This type of coastal zone is mapped in the geologic map of Qatar. More detailed mapping was achieved using TM band 1 mosaic covering the whole of Qatar peninsula and surrounding islands and waters(see Chapter 3: Figure 3.11). Moreover, the high spatial resolution airborne MEIS data provide the means to map the sand banks in detail especially in the high energy area of northwestern Qatar. It was possible to map the oil tar which sank in the shallow water of this area as a result of the process of sand sticking into the oil in the sand banks area (see Chapter 4: Figure 4.4 and Chapter 5: Figures: 5.26, 5.28 and 5.29).

Figure 6.10 Example of ESI = 7, offshore sand bars used by seabirds for resting areas during low tide.

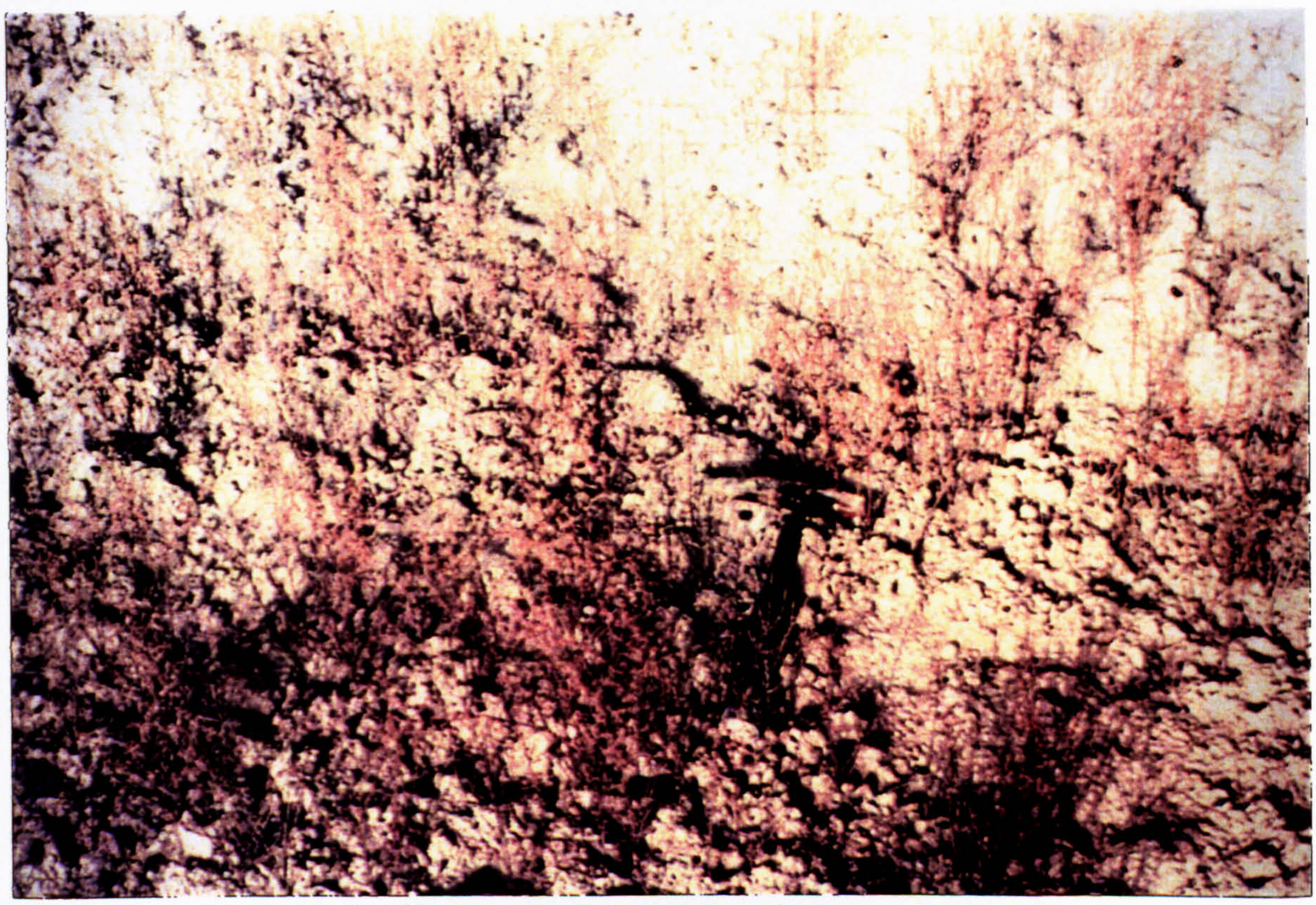


Figure 6.11 Example of ESI = 8, intertidal zone sediments distinguished by their light tan colour and many iron-stained root tubes and small holes.

6.6.3.8 Flat, compacted mud/silt intertidal zone

Intertidal zone sediments consist of the same sediments as the subtidal zone, but can be distinguished by their light tan colour and many iron-stained root tubes and small holes (Figure 6.11). The sediments tend to be more compacted toward the land and more muddy as is going toward the sea. The width of this zone is wide as being mapped by the airborne MEIS data in the extreme north of Qatar (Chapter 5: Figures 5.26 and 5. 29), no detail mapping for this type of coastal zone was found in the geologic and topographic maps of Qatar. The airborne MEIS data covering the extreme north of Qatar was visually interpreted to map the intertidal zone for the environmental sensitivity classification of northern Qatar.

During the field work, most of the ripraps found in north Qatar were placed in this wide intertidal zone. The zone is used by seabirds at low tide and fish at high tide for feeding area. The biological diversity and value of this type of the coastal zone are very high and need to be investigated in more detail in the future. Oil does not penetrate into the compacted sediment section of this zone , but it may penetrate into the more muddy sediment section where more small holes are existed (Figure 6.11). Even if the oil does not penetrate the surface it's sealing effect may cause a problem for subterranean organisms. Cleanup operations are very difficult and can be damaging. Oil maybe removed under the high energy conditions. The wide mud/silt intertidal zone in northern Qatar should receive priority for protection.

6.6.3.9 Sheltered lagoonal tidal flat

Sheltered lagoonal tidal flat in the west of Qatar is characterised by embayment of a semi-circular lagoon with intertidal area of algal mat that trap well-laminated sediments of calcareous muds. Inland of the algal flats is an extensive sabkhah which contains salt crusts between the periods of spring tides. The open water lagoon has an average water depth ranging between 2 and 3 metres and is connected to the Gulf through a relatively narrow outlet of maximum width of 1.5 km (see Chapter 3: Figure 3.10). The lagoon floor is covered by the same muddy sediments of the subtidal zone.

The sheltered lagoon is well mapped by the geologic and topographic maps of Qatar. However, no information is found in these maps for the intertidal area of algal mat. This area is considered to be high in biological activity. The whole sheltered lagoonal tidal flat is low in wave energy and during oil spills, oil may stay there for a long time. Therefore, this area should receive high priority for protection. Cleanup operations are very difficult and can be damaging.

6.6.3.10 Seagrass beds

Seagrass beds are only mapped using the airborne MEIS data covering the extreme north of Qatar (see Chapter 5: Figures 5.26 and 5.29). Seagrass beds are found colonising the muddy sediments of the subtidal zone south of the Ras Rakan island, extreme north of Qatar (see Chapter 3: Figure 3.7). During the field work this coastal zone area is found to be the feeding area for the most popular and expensive fish (*Siganus canaliculatus*) in Qatar.

This part of the coastal zone is of great biological value and low wave energy, therefore, must receive the highest priority for protection. During oil spills, oil may sink and cover the subtidal zone sediments and the seagrass beds, because the seagrass beds are still located subtidal in the sand banks zone where the sands stick into the oil and make it heavy so that it can not float on the surface of the water. As a result oil will start to sink and cover the seagrass beds. Cleanup operations are impossible in this situation, oil is must be prevented from interring this area.

6.6.3.11 Coral rock beds

Coral rock beds are more scattered in the shallow water of the north and northwest of Qatar. These coral beds are more vulnerable to oil pollution than any other parts of the northern Qatar coastal zone. Partly for the reason that they are more concentrated in the area which is characterised by high energy and found most polluted during the last oil spills in the Arabian Gulf.

When oil reach this area the sand tends to stick into the oil which makes it heavy so that it cannot float on the surface of the water. As a result the oil starts to sink and cover the coral beds. Cleanup operations are impossible and the same priority of protection that applied to the seagrass beds should be applied also here.

6.6.3.12 Sheltered salt marsh and mangrove

The sheltered salt marsh and mangrove in the northeastern Qatar is considered to be environmentally the most sensitive area along the Qatari coast. It is characterised by fine-grained carbonates and muddy sediments of the intertidal zone and complicated tidal channel system which is colonised by specific communities of halophytic plants such as mangrove, *Arthrocnemum glaucum* and algal mat (see Chapter 3: Figures 3.5 and 3.6; Chapter 5: Figures 5.30 and 5.31). This type of coastal area has been mapped by the airborne MEIS data (Chapter 5). Most of the existing maps in Qatar lack information on the salt marsh and mangrove.

The muddy sediments of this intertidal zone are found to be important for many marine animals such as crabs, gastropods and other organisms which feed on the organic material of the muddy sediments. Moreover, the mangrove and salt marsh form a notable breeding and resting areas for a large number of seabirds.

The sheltered salt marsh and mangrove in northeastern Qatar must receive the highest priority for protection not only from oil pollution but also from the intrusion of man. This area should be kept as national park where access is more controlled. During oil spills, oil may stay there for years and the cleanup operation is very difficult in this type of environment, because it may create more damage to the plant communities and erosion to the muddy sediments that are colonised by the plants. Therefore, preventing the oil from reaching this area by placing booms around it will help in keeping the oil away from the plant communities and the muddy sediments.

6.7 CONCLUSION AND RECOMMENDATIONS

Landfill, dredging and reclamation activities have been conducted systematically on a large scale in the Arabian Gulf. These activities have degraded the marine environments more than oil pollution. Unfortunately the areas chosen for these activities to happen are very high in biological productivity. It is time now and very essential to consider ways to preserve these habitats in the Gulf more seriously. An immediate moratorium should be imposed on all these activities in coastal areas of high biological productivity. In addition, there is a need for developing a comprehensive public awareness programme in the Gulf region to reduce and stop the collection of marine wildlife and eggs. Environmental management is clearly needed for the protection of the marine and coastal renewable resources in the Arabian Gulf.

Environmental sensitivity mapping is used for the establishment of a prioritised coastal zone management programme. Usually ESI mapping is associated with oil spill response and contingency planning. It has proved to be a useful technique for the identification of the environmentally sensitive areas and a means to set priority of protection. The concept of ESI mapping was enhanced recently to include the application of remote sensing and GIS technologies. Satellite imagery was used for the production of the planimetric basemap and shoreline information which are required for the ESI mapping.

However, the coarse spatial resolution of the satellite sensors tends to generate many mixed pixels in the image of mixed land cover types. Coastal zones require very high spatial resolution remote sensing sensors for detailed mapping. For the first time high spatial resolution airborne data (2 m) are used in the present study for the environmental sensitivity mapping of northern Qatar coastal zone. Three types of very sensitive vegetated habitat have been classified in the shallow water and fragile intertidal zone for the first time in Qatar by using the airborne MEIS data.

These sensitive habitats are incorporated into the ESI of northern Qatar and have been designated the highest priority for protection. The northern Qatar ESI has been created during this study by using airborne remote sensing data and conventional surveys. No ESI mapping existed before for Qatar, this is therefore considered to be an innovation. ESI mapping information will be imported into a GIS with other collateral data to produce a coastal information system for oil spill response planning in northern Qatar.

The coastal zone of northern Qatar is rich in biological diversity like other places in the Arabian Gulf. It supports a dense population of invertebrates and forms the nutritional basis on which the Arabian Gulf ecosystem depends. However, there is no literature dealing with the common species or their distribution and diversity in Qatar (Mohammed and Al-Khayat, 1994; Al-Khayat, 1996), and because of its richness and diversity it was not possible during the time of this research to carry out such survey and to include more biological information in the proposed ESI for northern Qatar. However, it is recommended that such a survey should be carried out at a national level for the whole coastal zone of Qatar as a matter of urgency. The biological information collected can then be incorporated in the proposed ESI developed during this research to reflect the diverse environments and marine habitats that are present in the coastal zone of Qatar and which respond differently to environmental pressures such as oil spills.

From the last comparison between the proposed ESI and the local experts, it seems that the local experts have good understanding about the value of the biological environments (such as salt marsh and mangrove) and the impact of oil spills on these sensitive environments. Therefore, they received very high rank in their questionnaires. However, they do not have clear understanding about the interaction of oil with every type of coastal environment and the concept of the Environmental Sensitivity Index. Therefore, short training courses in the ESI and oil spills response and planning are recommended in Qatar for the people that are involved in the planning, response and cleanup operations for combating the oil spills. Testing the proposed ESI for northern Qatar is also recommended and this can be included during the training courses.

CHAPTER 7

7. ASSESSING THE DESIGN OF COASTAL ZONE GIS FOR OIL SPILL RESPONSE PLANNING IN NORTHERN QATAR

7.1 INTRODUCTION AND BACKGROUND

Coastal zone vulnerability to maritime oil pollution is a complex multivariate problem characterised by both spatial and temporal trends, and as such is well suited to being handled within a GIS during the contingency planning phase (Clark, 1994). The traditional approach to evaluation of multivariate data for oil-spill contingency planning involved assembling the necessary material (maps, text, digital data and images) in hardcopy form, and manipulating it through manual techniques. Given the difficulty of applying rapid and consistent procedures within such an approach, the design of an information system to support contingency or operational response to oil spill has long been seen as an ideal. Gundlach and Hayes (1978) introduced the concept of mapping coastal vulnerability using spatial inventories of environmental and economic characteristics to provide a framework for the development of integrative indices. Although this approach was essentially manual, it established principles which have since been found to accord well with the needs of GIS procedures (Grice 1991; Jensen *et al.* 1990; Perkins 1989; Roper 1993; Collier *et al.*, 1995).

Clark *et al.* (1990) discussed the use of integrative ecological/habitat indices as inputs to a comprehensive assessment of oil spill vulnerability, and Clark (1994) demonstrated how GIS could be used to combine multiple layers of information using overlay techniques which allow the relative weighting (in terms of degree of influence on the outcome) applied to each individual layer to be controlled by the user. This provides a foundation for mapping oil spill vulnerability of the Qatari coast, provided that a combination of remote sensing and conventional surveys can be found to yield the necessary data.

7.2 ASSEMBLING THE NECESSARY DATABASE FOR THE NORTHERN QATAR COASTAL ZONE

Following the Gulf War oil spills, the need for detailed information on the sensitivity of the coastal zone environment of Qatar was recognised as being of prime importance. Information about the coastal zone environmental sensitivity was needed for the planning of oil spill countermeasures, but there was little available for the Gulf and Qatar. Most of the information in Qatar was in the form of geologic and topographic map sheets. These map sheets lack the information needed in the intertidal and shallow water zones and their sensitive habitats such as seagrass, salt marsh, and mangrove.

However, the information provided by these maps can still be used together with the high spatial resolution airborne data which was acquired following the Gulf War and field work to produce and establish the first sensitivity map for the coastal zone of northern Qatar. A large range of information can be obtained from the airborne MEIS data for the more sensitive areas of the coastal zone such as the seagrass, mangrove, salt marsh, and tidal flats which will be most severely impacted by the oil spills.

The ultimate goal of the ESI mapping (as discussed in Chapter 6) is to generate maps of coastal environmental sensitivity with respect to oil spills impact (Hayes *et al.*, 1980). These maps will provide the necessary information and assistance to oil spill coordinators in planning strategies for protection. Usually four types of information are included in ESI maps: planimetric basemap, shoreline sensitivity index, information on oil-sensitive wildlife, and access and protection features (Jensen *et al.*, 1990; Narumalani *et al.*, 1992).

The traditional approach to handling this information was in hardcopy form and manipulating it through manual techniques. Given the difficulty of applying consistent procedures within such an approach, GIS can be used now to support oil spill response planning.

However, the information on the coastal zone sensitivity must be available in digital format before applying the GIS technique can be used to support the planning strategy. In the next section of this chapter we will discuss how the necessary information was compiled, what sources were used in the compilation, and how the compiled information is reclassified according to its sensitivities to oil spills using the GIS system.

7.2.1 Conventional survey data

The conventional data used in the establishment of the present ESI mapping for northern Qatar coastal zone are composed of the topographic and geologic maps of Qatar at scale of 1:100 000. Most of the existing maps in Qatar are kept up to date using either aerial photographs or satellite imagery such as SPOT images. However, they still lack some information in the intertidal and shallow water habitats, therefore we use the airborne remotely sensed data to fill in the missing information.

A planimetric basemap consisting of a coastline was digitized for northern Qatar from the topography map using the TYDIG software package developed by TYDAC Research Inc. Information such as the roads network, oil pipelines, jetties and coastal towns and villages in northern Qatar are all derived from the topographic map and airborne MEIS data. Each of these types of information is stored in a separate layer in the GIS database of northern Qatar.

Not all the coastal areas in Qatar can be reached by the road network, so desert tracks must be used with fourwheel-drive vehicles in order to reach the various shorelines. Therefore, all the desert tracks have been digitized from the existing topography map and compiled with the road network in a separate layer. The road network including the desert tracks is of critical importance in oil spill planning, especially when crews must be dispatched to the various shorelines. In addition, other types of information such as the locations of jetties and coastal towns and villages are important for the initial placement of the booms and oil skimmers which are used during an oil spill.

Figure 7.1 shows the planimetric basemap of northern Qatar compiled from the conventional and remotely sensed data using TYDIG and SPANS GIS software packages. The map shows four types of information such as roads network including desert tracks, coastal towns, jetties and existing oil pipelines in northern Qatar, all of which are of critical importance for the oil spill countermeasures. The synthesis of this information in digital form is a significant innovation in its own right.

A coastal zone sensitivity index for northern Qatar has been developed using the existing geological map of Qatar, airborne MEIS data, and field work. Some information, in addition, on oil sensitive wildlife such as the locations and types of seabirds, fish and crabs has been collected during the field work. Qatar lacks the information needed on the coastal zone wildlife. Moreover, information on oil sensitive wildlife must ideally be collected by knowledgeable biologists and marine scientists.

The geology map is used to derive the information needed on the coastal geology for the sensitivity index. Information classes such as the sand banks, reefs, sand deposits, sabkhahs, beach rocks, bed rocks, and headlands have been digitized using the TYDIG digitizing software and are stored in a separate layer of information in the GIS database for northern Qatar (Figure 7.2).

7.2.2 Airborne remote sensing survey data

The airborne remote sensing data are composed of MEIS image mosaics and their final classification maps. In Chapter 5 we discussed the classification of MEIS data and how the final interpretation maps of the coastal zone habitats were derived. MEIS images were uniquely useful in providing the information needed in the intertidal zone and shallow water areas, and thus complete the sensitivity mapping picture of the coastal zone of northern Qatar.

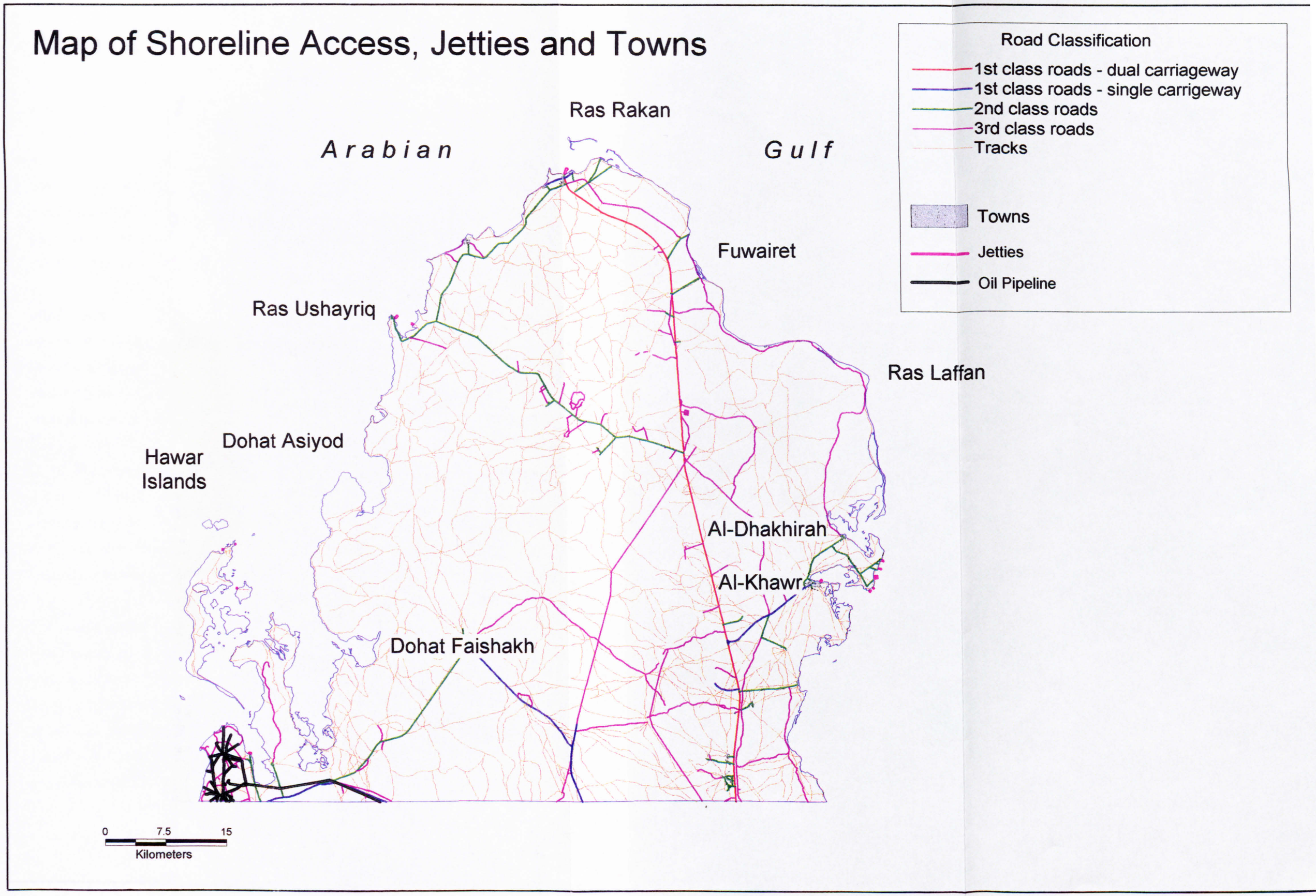


Figure 7.1 Basemap of northern Qatar shows the necessary information for oil spill countermeasures, especially when crews must be dispatched to the various shorelines.

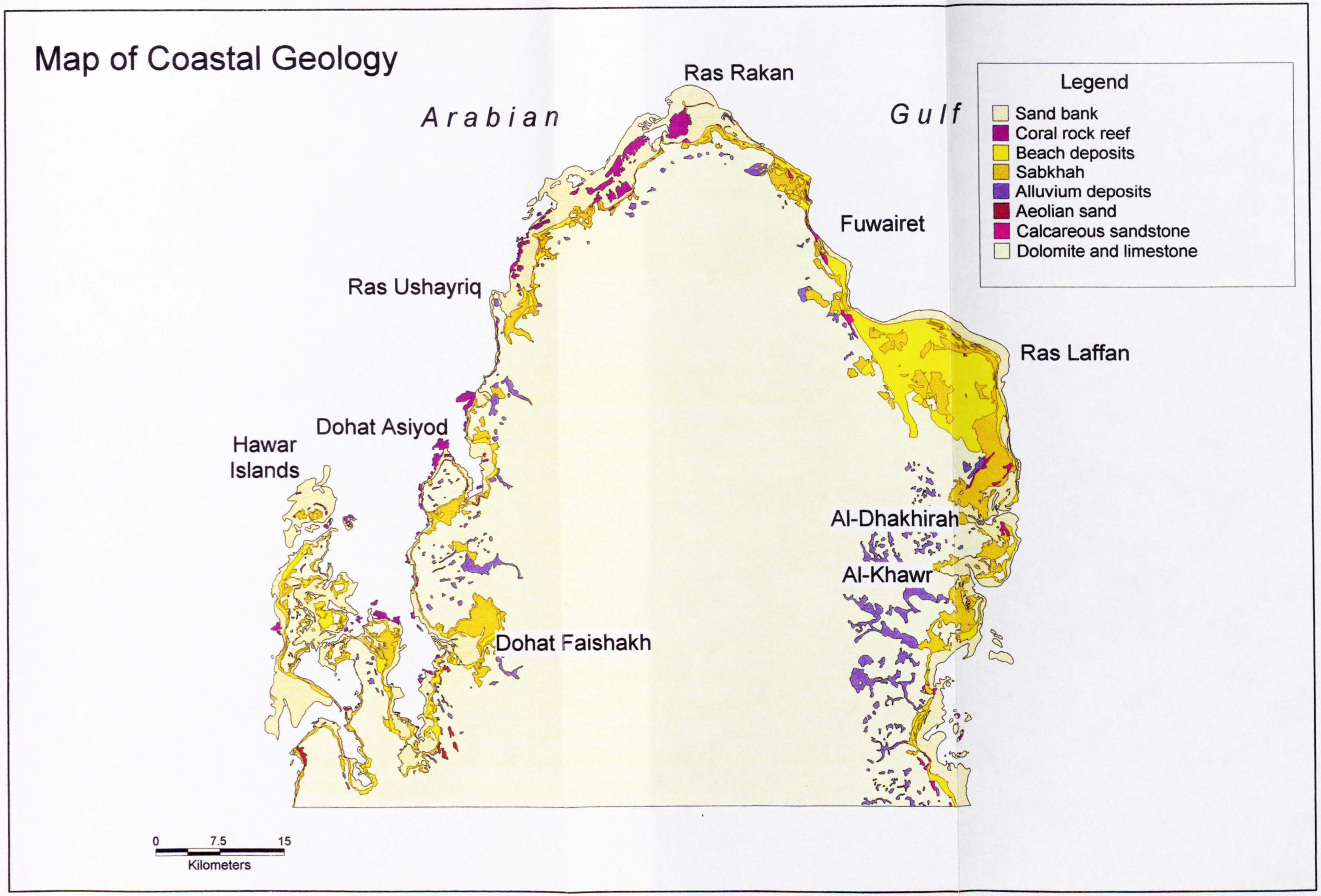


Figure 7.2 The coastal geology map of northern Qatar used to derive the information needed on the coastal geology for the sensitivity index.

The high spatial resolution MEIS images have allowed the seagrass beds in the coastal zone of extreme north of Qatar to be mapped for the first time in clear water (0.75 m deep). No information was previously available in Qatar about the locations of these beds, and during the field work, seagrass beds were found to be a feeding area for the most popular and expensive fish in Qatar (*Siganus canaliculatus*). The salt marsh in the extreme north of Qatar was found to be missmapped as a coral reef in the previous maps of Qatar. This is possibly due to the use of black-and-white aerial photographs for the interpretation and generation of the maps, and also to the similarity in shape and texture between the salt marsh and the reef which might introduce some confusion in the final interpretation.

MEIS images are used to fill in the information gap in the coastal zone and at the same time update the existing map information in Qatar. In addition, during the field verification of the remotely sensed classification results, we found that the salt marsh and the surrounding intertidal areas and sand bars were used as a resting areas by the seabirds such as *Socotra cormorant* and *Kentish plover*.

In the north east of Qatar MEIS images are used to map the sensitive mangrove, salt marsh, and intertidal areas. Very detailed maps of these information classes were produced (see Chapter 5). In addition, all the new manmade features in the coastal areas such as the roads, seawalls, ripraps and jetties were also mapped using the MEIS images. All the information derived from the remotely sensed data have been digitized.

The coastal habitats are digitized and stored in a separate layer, while the manmade features such as the roads, seawalls and jetties are compiled with the same types of information layers derived from the topography map. The seawalls and ripraps are compiled with the town information layer derived from the topography map of Qatar. Now all the compiled information layers for the coastal zone of northern Qatar are in digital format ready to be imported to the SPANS GIS system for further manipulation and generation of the ESI map of northern Qatar coastal zone.

7.3 GIS DATA MANIPULATION AND CREATION OF THE ESI MAP OF NORTHERN QATAR COASTAL ZONE

Before we start a discussion of the creation of the ESI map of the northern Qatar coastal zone, we should consider in more detail how the information in the coastal zone was captured and how the digital database was created. As we mentioned earlier, the TYDIG and SPANS software packages developed by TYDAC Research Inc. were used for capturing and manipulating the coastal zone information of northern Qatar. Two types of information are captured, lines and areas (Figure 7.3)

Figure 7.3 illustrates how the digital database were created and the production of the ESI map. The lines information are composed of the coastlines of northern Qatar, the roads network, oil pipelines and jetties. Each is digitized using TYDIG in a separate layer of information. The layers are then exported to SPANS format and imported to SPANS GIS for editing the lines information. Topology, in addition, is built for each type of line information layer. For example, the road network is classified according to their size and type such as first class roads with dual carriageway, first class roads with single carriageway, second class roads, third class roads (surfaced and unsurfaced) and desert tracks. The line information is then exported to the MapInfo software package for further cartographic works.

Figure 7.1 shows the output result of several information layers compiled in one planimetric basemap. This displays the information that would be needed in oil spill crises when crews must be dispatched to the various shorelines for the initial placement of the booms and skimmers which are used during an oil spill. For example, which is the best route to follow and what type of roads to use and is there any facility for launching the booms and skimmers in that part of the shoreline?

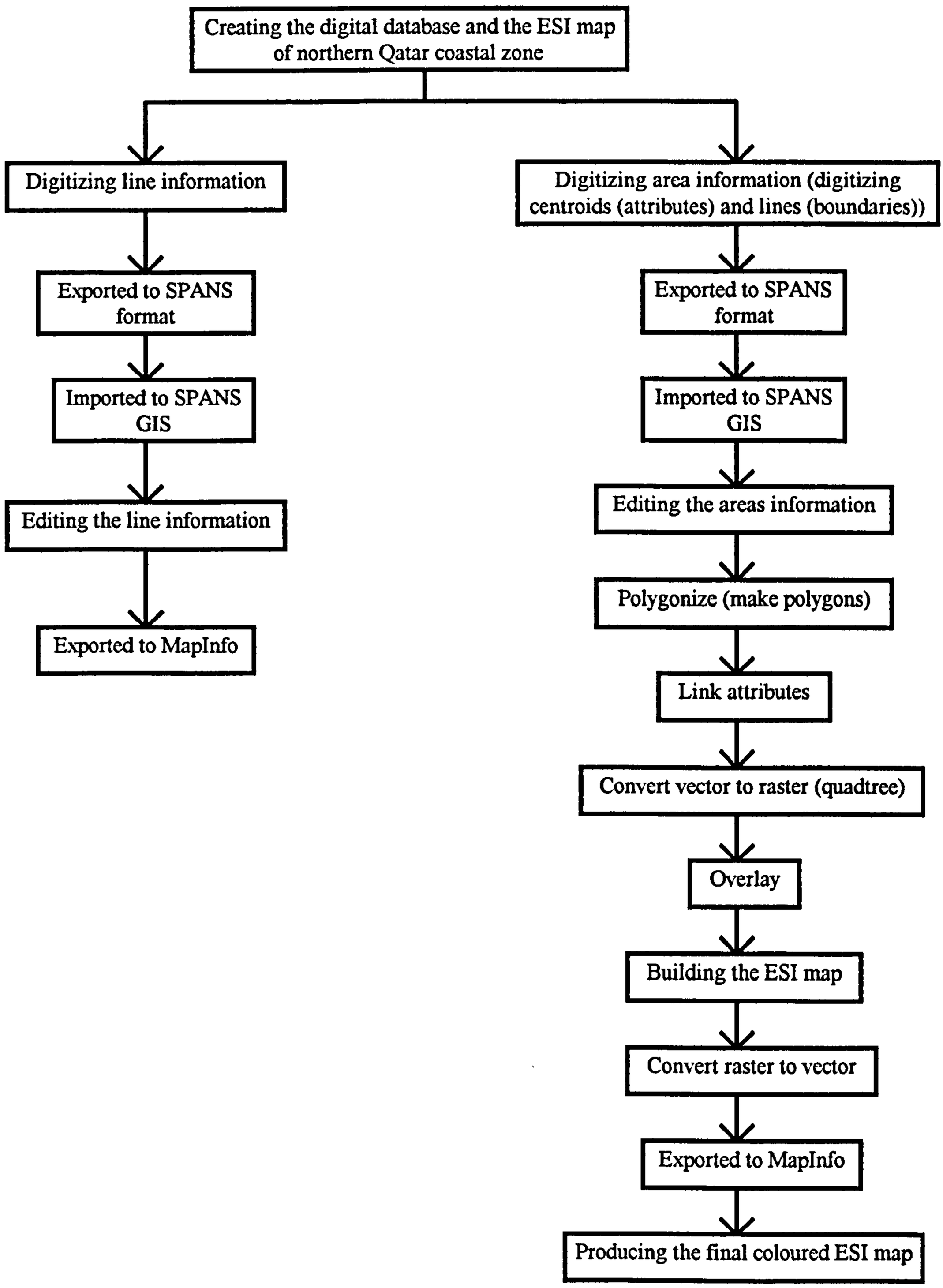


Figure 7.3 The flow chart of creating the digital database and the ESI map.

The areas are digitized as lines (boundaries) with centroids (to which the polygon attributes are linked) using the information derived from the geology map, airborne MEIS data and field work. The information is then exported to SPANS GIS and imported to SPANS GIS for editing, polygonizing (making polygons) and linking attributes. Some of the information classes were in the form of lines such as the seaweed (collected from the field work), headlands (collected from the geology map) and riprap (collected from the MEIS images). Therefore, a buffer is built for each of these classes in order to form an area type of information for analysis. The digitized information is then converted from vector to raster (quadtree). The information derived from the airborne MEIS data and field work are overlaid on the coastal geology map to make one map that exhibits all the characteristics of the northern Qatar coastal zone (Figure 7.4).

Figure 7.4 shows the coastal zone information classes that have been compiled from the geology map, airborne MEIS data and field work. However, these information classes are still not in the form of coastal zone sensitivity index. The proposed ESI classification developed in Chapter 6 (Table 6.3) for northern Qatar coastal zone is used then to reclassify the coastal zone information classes (map in Figure 7.4) according to shoreline interaction with the oil, oil persistence in that environment and the extent of biological damage. The map is then converted from raster to vector and exported to MapInfo software package for further cartographic works and assigning of colours for the different sensitive classes.

The different oil-sensitive classes are then colour coded according to their sensitivity. For example, classes with high sensitivity index are colour coded with the red colour in order to highlight that particular sensitive part of the coastal zone and at the same time to show the response team the areas at risk which would need the most protection when the incident of oil spill is happened.

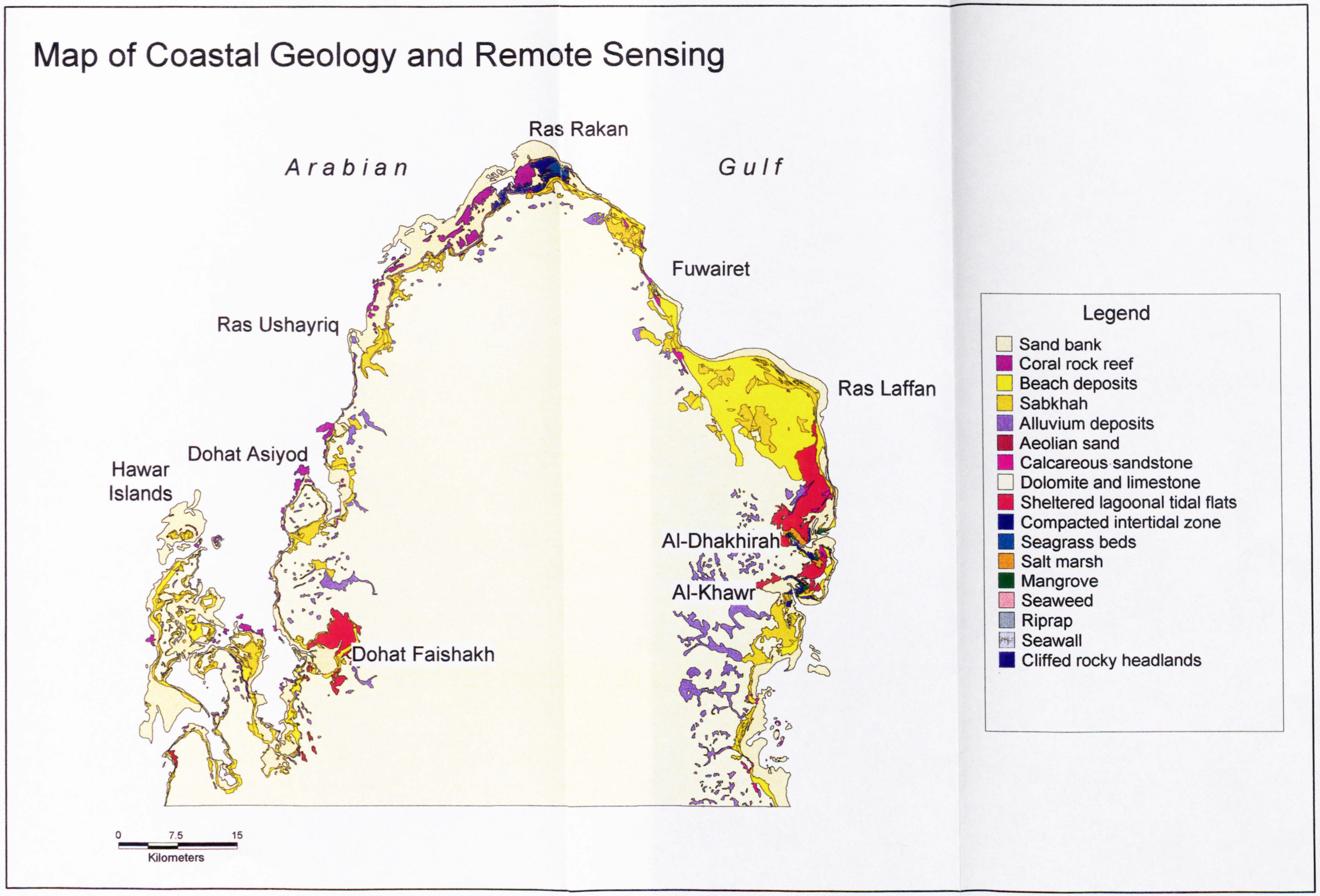


Figure 7.4 The compiled information on the coastal zone resources of northern Qatar from the geology map, airborne MEIS data and field work.

For example, in northern Qatar coastal zone, the sensitive classes such as the mud/silt intertidal areas, sheltered lagoonal tidal flats, seagrass beds, coral rock beds, and sheltered salt marshes and mangroves are all coloured in red colour to show that these areas of the coastal zone must receive high priority for protection. In addition, this priority colour shows that cleanup operations are very difficult and can be damaging (see Chapter 6, Table 6.3 and Section 6.6.3).

Figure 7.5 shows the final ESI map of northern Qatar coastal zone as interpreted from the conventional survey and remote sensing with the shoreline access and the areas that known to be for seabirds and fisheries which are depicted by symbols on the map. This map should provides a guidance for an oil spill response and planning in Qatar and at the same time the access to information for the personnel in charge of cleanup operations.

In addition, environmental sensitivity mapping is a technique that can be used not only for oil spill response planning, but also for the establishment of a coastal zone management programme or plan. However, more information can still be added such as on the oil sensitive wildlife which must be collected by knowledgeable biologists and marine scientists. This can be recommended for the future works in Qatar to carry out a national survey in the oil sensitive wildlife along the Qatari coastal zone. The map represent the culmination of the technical manipulation and conceptual discussion of the previous chapters, and is an innovative operational fusion of remote sensing and GIS technologies.

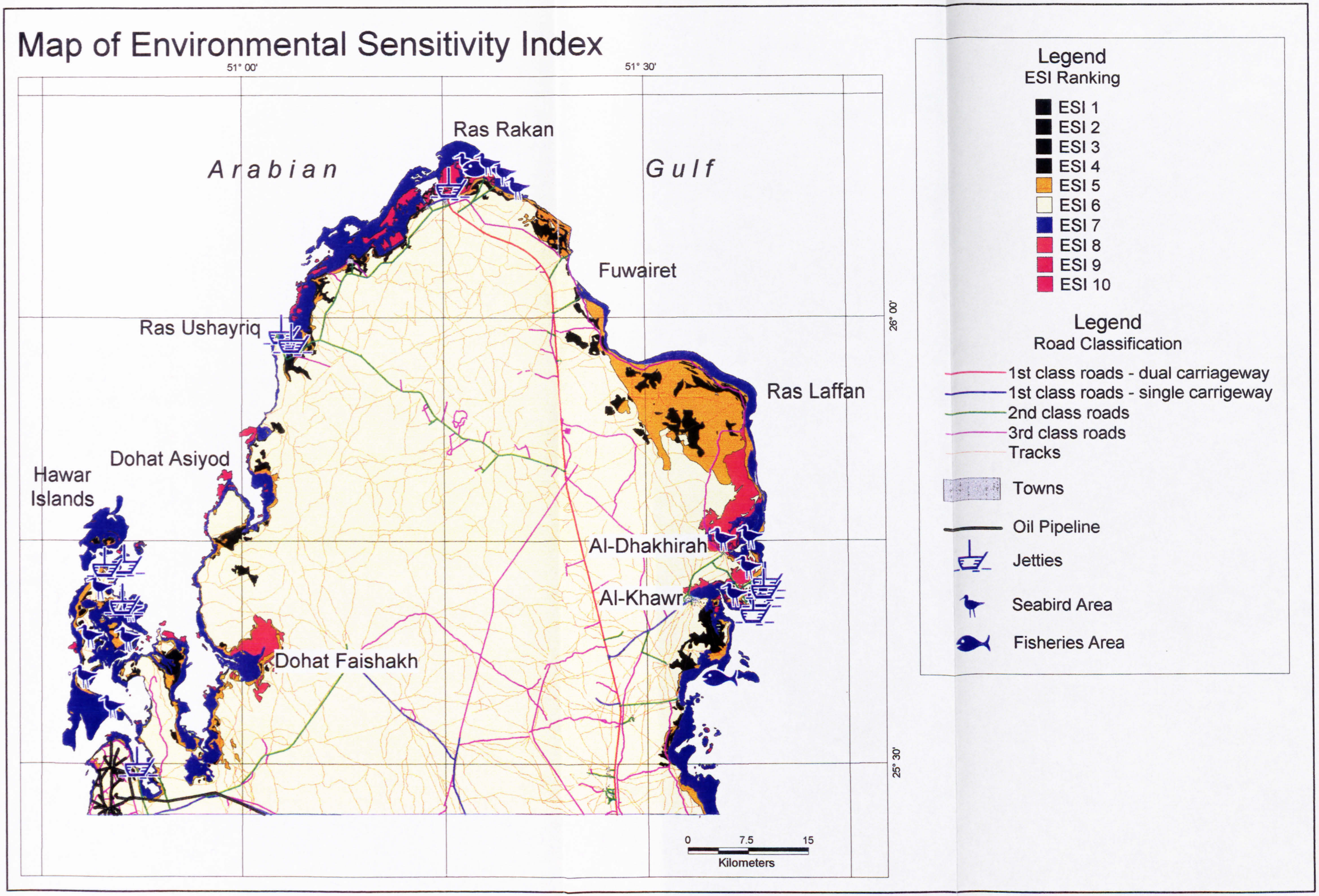


Figure 7.5 The final ESI map of northern Qatar coastal zone showing the guidance for an oil spill response and planning in Qatar and the access to information for personnel in charge of cleanup operations.

CHAPTER 8

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 INTRODUCTION

The final conclusions and recommendations of the research are presented in this Chapter. First, is the presentation of the problem of oil spills in the Arabian Gulf as a continuous threat to the fragile and vulnerable coastal zone of northern Qatar. Second, is the need for Environmental Sensitivity Index (ESI) mapping in Qatar for the protection of the fragile coastal zone environment and the planning of oil spills response. Third, is the advantage of using high spatial resolution airborne remote sensing and GIS systems to enhance traditional approach of ESI mapping. The traditional method of mapping the coastal features planimetrically by viewing the terrain obliquely was very difficult, especially in complex coastal zones, and can introduce some errors in the final maps. Fourth, is the evaluation of multivariate data for oil-spill contingency planning. This involves assembling the necessary material (maps, text, digital data and images) in hardcopy form, and manipulating them through manual techniques. Given the difficulty of applying consistent procedures within such an approach, it has been found to accord well with the capabilities of GIS procedures. Finally, the Chapter concludes with a set of recommendations for future work in the Gulf and Qatar regarding coastal zone management and ESI mapping using remote sensing and GIS systems.

8.2 THE PROBLEM OF OIL SPILLS IN THE ARABIAN GULF

Oil spills appear likely to continue as a major threat to the fragile coastal environment in the Arabian Gulf as long as there is a global reliance on petroleum products. Oil exploitation will continue to be the main source of income in the Gulf. As a result, oil spills and leaks have long been a problem for the Gulf coastal zone environment. In addition, new development such as industries, especially oil-related industries, which have been established to diversify the Gulf economy have also intensified environmental pressure in the Gulf region and increased the impact on coastal environmental quality.

The Gulf is a nearly landlocked sea, and the only compensation for the water lost by high rates of evaporation comes from the net inflow from the Indian Ocean through the narrow Strait of Hormuz. This causes a system of counter-clockwise surface currents parallel to the Iranian side. Subsurface currents occur on the Arabian side as the dense water sinks and then flows out through the Strait of Hormuz under the less dense incoming water. Moreover, the Qatar peninsula projects 180 km due north from the Arabian shore into the Gulf. With the meteorological and hydrological conditions in the region, this situation makes the Qatar peninsula particularly vulnerable to any oil spills that might occur in the Arabian Gulf, especially the northern half of the peninsula where the characteristics of the coastal zone influence its susceptibility to oil pollution.

The northern half of Qatar peninsula reaches almost to the middle of the Gulf's waters. Any oil spills that might occur near the shore and/or offshore in the Gulf are influenced by the counter-clockwise currents system in the Arabian Gulf and are moved toward the coastal zone of northern Qatar. For these reasons, the coastal zone of northern Qatar is found to be more heavily polluted by oil than any other part of the Qatari coastal zone. In addition, the northern Qatar coastal zone is composed of very sensitive and fragile coastal zone environments which are not be found in the southern half of the peninsula. These sensitive and fragile environments can easily be damaged by oil spills in the Gulf region.

Oil spills will continue to occur in the Arabian Gulf region and northern Qatar will always be vulnerable to oil pollution. Access to information like the location of the spill, the potential area of impact, the environmental sensitivity of the impact area, and the available resources to combat the spills are very important for personnel in charge of cleanup operations in order to achieve the aim of decreasing impacts associated with an oil spill. In Qatar, none of this information is available for personnel in charge of cleanup operations, therefore, creating the Environmental Sensitivity Index (ESI) mapping for northern Qatar is considered an essential first step.

8.3 THE NEED FOR ENVIRONMENTAL SENSITIVITY INDEX (ESI) MAPPING

Protection of the fragile coastal zone environment in northern Qatar is essential. The protection needs first the knowledge of the different habitats environment that exist in the coastal zone areas. Which resources are more vulnerable to environmental pressures and damage and establishment of protected areas? Since this information is not available for most of the coastal zone of Qatar, ESI mapping of the coastal zone habitats is highly essential for the protection and better management of these habitats. ESI mapping, which is being increasingly used around the world for oil spill countermeasures, provides a technique to assist response coordinators and government agencies in planning strategies for protection. However, Qatar is amongst those countries surrounding the Arabian Gulf that has no ESI mapping for its fragile coastal zone environment, although the Arabian Gulf is known to be among the most polluted seas in the world from oil pollution.

The aim of the present study was to develop ESI mapping for northern Qatar using modern technologies such as remote sensing and GIS. The methodology used to yield the necessary information for the creation of the ESI was based mainly on the analyses of remotely sensed data and conventional surveys. The sensitivity classification of the coastal zone was extracted from high spatial resolution airborne MEIS data, geologic and topographic maps of Qatar, available literature and field work. In addition, the ranking of the coastal zone sensitivity types was based on expert opinion on known interactions of oil with various coastal types which have been observed over the past years. The most sensitive environmental areas were considered to be the salt marsh, mangrove, seagrass, and coral

rock bed, while the least sensitive areas in Qatar where found to be manmade features, drifted seaweed and wood beach, and rocky headlands. It was impossible to include more biological attributes in the proposed ESI because the coastal zone of northern Qatar is rich in biological diversity and there is no literature dealing with the common species or their distribution and because of its richness and diversity it was not possible during the time of this research to carry out such survey. It is recommended that such a survey should be carried out at national level for the whole coastal zone of Qatar as a matter of urgency.

The proposed ESI was assessed by local experts in Qatar to elicit opinions on the ESI ranking of the various coastal zone types. The result showed that the local experts have a good understanding of the value of the biological features (such as salt marsh and mangrove) and the impact of oil on these sensitive environments. Therefore, these categories received high ranks in their questionnaires. However, they did not have clear knowledge about the interaction of oil with all other types of coastal environment. It has been suggested that local training in oil spills response is very important and needed in order to have better planning and response for combating the oil spills. This can be achieved by applying short training courses in oil spill response for the people that are responsible for the protection of the marine and coastal environments in Qatar.

8.4 THE POTENTIAL OF HIGH SPATIAL RESOLUTION AIRBORNE REMOTE SENSING FOR ESI MAPPING

Remotely sensed data have been a major source of information (and are likely to continue to be) for the diverse nearshore marine and coastal environments. Research applications in many of the applied fields have turned increasingly to remote sensing for a partial and/or full solution. The synoptic coverage, spectral information and cost-effectiveness provided by the remotely sensed data make it ideally suited for studies and mapping of habitats in the coastal zones. Remotely sensed data have been used world-wide for studying and mapping sensitive marine and coastal habitats such as salt marsh, mangrove, seagrass and coral reef. In addition, they make a very important source of data for the development of coastal zone GIS.

As discussed in Chapter 2, although data derived from remote sensing are increasingly being utilised as a data source in GIS, none of the previously discussed studies for the coastal zone were actually using remote sensing as a data source for the GIS except those by Jensen *et al.* (1990); Narumalani *et al.* (1992); and Jensen *et al.* (1992). They discussed the utilisation of satellite data as a source of data for the environmental sensitivity mapping of the coastal areas and as input in a GIS system for interfacing it with a relational database for rapid retrieval and querying. This therefore allows management decisions on oil spills to be made in real time.

However, the coarse spatial resolution of satellite sensors tends to generate many mixed pixels of ground materials in the image. In other words, decreasing the size of the ground instantaneous field of view (GIFOV) of the sensor for a heterogeneous scene increases the variance in the data and makes purer pixels more likely (Boardman, 1994). Therefore, in principle coastal zone areas would require a higher spatial resolution remote sensing sensor for detail mapping of their complex environment. Many of the future satellite programmes are moving toward the higher spatial resolution sensors to fill the needs of high spatial resolution satellite data (see Chapter 2). Today, high spatial resolution airborne sensors can be used in such mapping. However, when the data cover large areas, large volumes of digital data are generated which make automated analysis and handling of the data very difficult. Such issues have not been tackled before, especially in the ESI mapping of the coastal zone.

8.4.1 The advantage of 2 m pixel resolution for the ESI mapping

The largest primary scale of topographic mapping available for Qatar was 1:100,000, all larger scales being photo-enlarged from this. This fact may suggest that Landsat TM would be a suitable data source for the coastal sensitivity map, however, this was found not to be the case. Landsat TM images were used in the early part of this study (e.g. see Figure 5.1), and previous research by myself and my colleagues in Qatar has used Landsat TM for geological mapping(Khamis, 1989; Khamis *et al*, 1990; Akbar, 1989; Akbar *et al.*, 1990; Akbar, 1995), but Landsat TM (and SPOT XS) were found to be insufficiently detailed for

the present purpose. The reason for this is that many of the classes in the coastal zone are defined by the particular combination of very small objects (e.g. small creeks and mangrove canopy) rather than objects which are homogeneous over the 30m pixels of the Landsat TM. Although the polygons in the final map could have been shown on a Landsat TM image, the labelling of the polygons required finer spatial resolution data - the question was, how fine? To help answer this question, the 2m resolution data were degraded to 10m and re-classified. The problems with the MEIS sensor and the inadequate mosaicking prevented a full evaluation of the 10m data, but it was clear than many of the classes could be identified from this level of detail, and this suggests that future very high resolution satellite sensor data may be ideal for this task. However, for the present purpose, 2m MEIS data are readily available and a procedure has been derived to present them in a manageable form, so there is no incentive to degrade these data unnecessarily. The important point is that data at a finer resolution than the final scale map produced were essential in order to label the classes accurately.

A second point regarding the various scales of data used in the study concerns the geometric correction of the images. Clearly, if the only topographic maps available are at 1:100,000 scale, this will define the precision with which ground control points can be located. This means that it would have been inappropriate to produce a map from the MEIS data at any larger scale that 1:100,000, and further, this prevented the location of individual pixels on the ground for accuracy assessment purposes. When interpreting the MEIS data, the final scale of the map was always kept in mind and this was used to help generalise the interpretation. Any geometric errors in the registration of the MEIS data were of no consequence when overlain on the 1:100,000 final scale map.

The present research dealt with a new study approach using very high spatial resolution airborne data covering large areas for ESI mapping of the fragile coastal zone habitats for oil spill response and planning. At present Qatar has full recent (date April 1991) coverage of very high spatial resolution airborne MEIS data (2m) for the whole coastal zone of the country. This was acquired to provide a detailed source of information for ESI mapping in Qatar and the planning of oil spill counter measures. However, the nature of this airborne dataset represents the unique problem of comprising very large volumes of digital data

because it was scanned at very high spatial resolution (2 m pixel resolution) and covered large areas. Handling and using such large volumes of digital data for ESI mapping are very difficult tasks that have not been investigated before this study. This problem will also face the future programmes of the satellite higher spatial resolution sensors.

The airborne MEIS data have revealed valuable information in the intertidal and shallow water for the ESI mapping such as the mapping of seagrass beds, salt marshes and mangroves, which were difficult or impossible to map using coarse spatial resolution satellite sensors and conventional surveys. In addition, the high spatial resolution of the MEIS sensors was significant for mapping the oil tar (resulting from the last oil spills in the Gulf in January, 1991) in the shallow coastal water of northern Qatar. MEIS images revealed significant information about the behaviour of oil spills when they reach the shallow water of northern Qatar.

We understand now that most of the light chemical components of crude oil are evaporated by the sun, which makes the oil thicker which then breaks into small pieces and finally formulates oil tar. The oil tar is carried by the wind and surface currents in the Gulf to the shallow coastal water of northern Qatar. This area is known to be a high energy and sediment movement area, therefore when the oil tar reaches the area a lot of sediment sticks into it which makes the tar so heavy that it cannot float on the surface of the water. As a result, most of the oil tar sinks in the shallow water covering all types of life beneath. Some of the oil tar still can reach the shore line of northern Qatar and produces very severe damage, as happened during the Gulf War.

Four types of analyses were applied to the MEIS data in order to find the best approach to handling the large volume of digital data and at the same time revealing the information needed in the coastal zone for the ESI mapping. The first analysis assessed was image classification technique (unsupervised and supervised) which was applied to the airborne MEIS data in order to classify the vegetated habitats in the coastal zone areas for the ESI mapping. The second analysis was a resampling technique followed by classification in order to overcome the problem of large data volume. The third technique was image compression and visual interpretation of the compressed images for the production of the

ESI mapping. Finally to make the interpretation of the remotely sensed data fully automated and at the same time to handle the large volume of the digital data, spectral pixel unmixing analysis has been applied.

8.4.2 Image classification

Image classification was performed only in three bands of the data (RGB/3, 2, 8), since the infrared colour composite image of these three bands was enough to show a great deal of information about the vegetated habitats in the coastal zone of northern Qatar. The large volume of digital image data prevented use of all eight spectral bands of MEIS (2 m pixel resolution) at one time during the classification. The resulting classified maps showed much better representation of the real habitats on the ground, because decreasing the size of the ground instantaneous field of view (GIFOV) of the sensor increases the number of classes that can be identified in the scene and makes purer pixels more likely (Boardman, 1994). This was confirmed by a number of different coastal zone habitats being mapped using the present high spatial resolution airborne MEIS data, which would have been impossible using present satellite sensors.

However, we are classifying a very complicated environment (the coastal zone) where water will always be present. In addition, the characteristics of the coastal zone habitats in Qatar, being small in size and scattered over large distances, introduced some "salt and pepper" effects in the final classification maps. Moreover, we still have not used the potential benefit of incorporating all eight spectral bands in the classification, nor overcome the problem of reducing the large volume of the digital data in order to reduce the time of computation and make the interpretation and production of the thematic maps more possible. Reducing the data volume present in the MEIS scenes without losing much of the information in the data was considered as a major problem that should be solved first before starting the interpretation of the data and the production of the final thematic maps.

8.4.3 Image resampling

Resampling techniques were applied to the MEIS data to produce 10 m pixel resolution data to be used in the classification. By doing this we reduced the size of the image file to a manageable size for the computer, but at the same time we lost the advantage of the 2 m pixel resolution. However, it was then possible to use all eight bands of the resampled MEIS data at once in the classification. However, the result was rather noisy and showed a "salt and pepper" effect plus a disjointed appearance caused by the resampling technique. In addition, the artifact caused by mosaicking the adjacent flight lines was very obvious in the final classified map when all eight bands of MEIS data were used together in the classification. To overcome this artifact and remove data redundancy from the original imagery, image compression technique was applied to the MEIS data.

8.4.4 Image compression

Image compression was the experimental technique applied to the MEIS data to overcome the problem of large data volume and at the same time to produce high quality hardcopy format of the airborne data to be visually interpreted for the generation of the coastal zone habitat map. The compression algorithm removes redundancy from the original image which reduces the size of the output file to very small and produces very high quality image and hardcopy. However, image compression is known to be a technique where some information is usually lost during the encoding to achieve high compression ratios. In fact almost every operation of converting an image is a lossy technique. For instance, some information is usually lost when we try to display, scan, digitize and print an image. However, the loss of information is generally very small. Very recently, even before completion of the writing up of the present thesis, image compression has become a routine available in image processing software packages (such as ENVI software package).

Two types of image compression algorithms (GIF and JPEG) were applied to the MEIS data. The resultant image of GIF compression appeared to have some "salt and pepper" effect especially in the intertidal and shallow water areas, which made the final image look more blocky. However, the resultant image of the JPEG compression appeared very close

to the original image with very small loss of information. Detailed mapping was achieved for the very sensitive resources to oil spills such as the salt marsh, mangrove, seagrass, and intertidal area by using visual interpretation of the compressed image. Therefore, image compression could be used as one solution to handling the large volume of digital remote sensing data. Image compression such as the JPEG algorithm worked very well for the airborne MEIS digital data covering the coastal zone of Qatar.

8.4.5 Automated spectral pixel unmixing analysis

Finally, to make the interpretation of the remotely sensed data fully automated, and produce abundance images for the coastal zone habitats that can be used directly in the ESI mapping, and at the same time to handle the large volume of data, we applied spectral pixel unmixing. Usually a high degree of correlation is exhibited in the many, narrow bands of the remotely sensed data such as the airborne MEIS data set. Automated spectral pixel unmixing analysis first compresses the remotely sensed data to separate the signal from much of the noise, and then identifies the smallest dimensions that adequately express the variability of the data which then reduces the computational requirements for subsequent processing of the data. This has overcome the problem of having a multi-spectral data set that is very large and at the same time covers very large areas of the Earth's surface.

The resulting bands from the analysis showed that the first three appear spatially coherent while the rest were very noisy with obvious mosaicking artifacts. The first three bands indicated the inherent dimensionality of the data and were used subsequently in the analysis to extract the endmember spectra to be used later for the automated pixel unmixing. A spectral library of endmember spectra was built for the study area to be used in the unmixing analysis. The output results of the unmixing are usually presented in black-and-white images, one for each endmember spectrum where the brighter pixels represent the higher abundance for that endmember. However, the resulting images from the spectral unmixing for the study area were very highly affected by the mosaicking that had been applied to the whole data set. We concluded that the results would have been better if the data were not mosaicked.

For future applications of remote sensing in Qatar, automated spectral pixel unmixing analysis is highly recommended for handling and classifying large amount of digital remote sensing data especially when the future satellite programme are going towards higher spatial resolution data and Qatar requires these types of data for the future mapping and updating of the existing maps. A spectral library of all surface materials can be generated using linear spectral unmixing. This will help to overcome the problem in Qatar of using remotely sensed data to classify surface materials that have small spatial resolution and are distributed over large distance. In other words it will overcome the problem of always having mixed pixels in the final classification of the remotely sensed data. The spectral library of surface materials and spectral unmixing also can be used to classify even coarser resolution data covering Qatar such as the present satellite data once the spectral library of all surface materials has been built.

8.5 GIS SYSTEM FOR OIL SPILLS OPERATIONAL RESPONSE

The traditional approach to handling the ESI maps, text, digital data and images was in hardcopy form and manipulation through manual techniques. Given the difficulty of applying consistent procedures within such an approach, a GIS system has been used to design and support the operational response to oil spills in northern Qatar coastal zone. The compiled information on the coastal zone sensitivity of northern Qatar (from the remote sensing, conventional survey and field work) was converted to digital format in order to be manipulated by the GIS system. The GIS then reclassified this information according to its sensitivities to oil spills using the proposed ESI developed for the northern Qatar, and a GIS ESI map for northern Qatar was created.

The GIS ESI map illustrates all the information needed by the personnel in charge of the cleanup operations. It illustrates the coastline of northern Qatar and highlights the most sensitive sections of the coastal zone with red colour in order to show the response team the areas at risk which would need the most protection during an oil spill. In addition, it illustrates the other relative information such as the location of the road network, jetties and urban areas along the northern coast of Qatar which are needed for the initial

placement of the booms and oil skimmers used during the oil spills for protecting those most sensitive sections of the coastal zone.

8.6 CONCLUSION

Little information is available in the literature for the Gulf region (or maybe has not been started yet) regarding the marine and coastal zone management plan and ESI mapping. Table 8.1 shows some of the information that was found in the literature, and it appears that the present ESI mapping for the northern Qatar coastal zone is comparatively more advanced (Appendix 2). Recently United Arab Emirates (UAE) has started a project with GeoData Institute, University of Southampton for ESI mapping of the whole shoreline using Landsat TM imagery. This project is almost in the finishing stage and production of the final ESI maps.

Country	Marine and coastal zone management plan	ESI mapping
Bahrain	?	?
Kuwait	Yes	?
Iran	Yes	?
Iraq	?	?
Oman	Yes	Yes
Qatar	No	Yes
Saudi Arabia	Yes	?
United Arab Emirates	?	Yes

Table 8.1 The situation of marine and coastal plan and ESI mapping in the Arabian Gulf.

It has been found that having a management plan in the Arabian Gulf dose not mean that it will be used effectively to conserve the marine and coastal zone fragile environment. According to Sheppard *et al.* (1992) in Saudi Arabia, for example, despite their known bioeconomic importance, mangroves degradation and loss is still occurring in some coastal areas while it has been transported with some success on the other coastal areas of Saudi Arabia.

It is time now to consider the preservation of the Arabian Gulf coastal zone habitats more seriously. Environmental management is clearly needed for this protection, but managing the genuine complexities inherent in natural systems requires an interdisciplinary approach rather than sectoral. It requires understanding of the system complexity and behaviour in order to determine the future environmental needs and responses. In addition, in order for coastal environmental management to proceed in the Arabian Gulf, it requires as a first step a detailed survey of the coastal zone to identify the distribution and use of coastal resources. Which resources are more vulnerable to environmental pressures and damage and establishment of protected areas? This can only be accomplished by sensitivity assessment and mapping, which is being increasingly used around the world for the coastal zone management. Environmental Sensitivity Index (ESI) mapping provides a technique to assist response coordinators and government agencies in planning strategies for protection from oil spills. In the absence of oil spills, ESI maps can still be used for the establishment of a coastal zone management programme or plan.

Such a management approach cannot be implemented unless the local people and government agencies realise the importance of the conservation of the coastal zone fragile environments. Therefore, the development of a comprehensive public awareness programme in the Gulf region by using posters, audiovisuals and other materials, is essential to enhance the coastal environmental management in the Arabian Gulf region. In addition, there is a real need for environmental wildlife laws and regulations in the Gulf region for the protection of marine wildlife. All of these should help to constrain the environmentally degrading operations in the Gulf such as the landfill, dredging, reclamation and human predation of marine wildlife and eggs. Environmentally, coastal zone activities such as landfill, dredging and reclamation are extremely damaging operations that must not occur within sensitive parts of the coastal zone.

Remote sensing techniques should be considered in the applications of the complex environmental problems in the coastal zones of the Gulf. Remote sensing is generally just one tool, which should be combined with other spatial and temporal data in a geographical information system (GIS) for effective management of coastal zones. The combination of remotely sensed information with other (geographical) information in a GIS is essential for

integrated environmental analyses (Appendix 2). The GIS also has the potential to allow management decisions on oil spills to be made in real time.

Coastal zone conservation is a regional environmental management problem rather than an obligation of a single coastal country. The need for international environmental management agreements between the Gulf's countries is essential, since the Gulf is an almost enclosed waterway with resources that cross national boundaries. ESI mapping should be standardised and begin at the national level first, then all the national ESI information should be compiled to form a regional ESI map to serve the Arabian Gulf as a whole. In this way the technical advances made within this thesis can serve the needs of coastal peoples throughout the Gulf.

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APPENDIX 1

OPINIONS OF LOCAL EXPERTS IN QATAR ON THE ESI RANKING OF THE VARIOUS COASTAL ZONE TYPES IN QATAR

1. Exposed, cliffed rock headlands				
Vulnerable to oil	Sensitive to oil	Cleanup		
3	5	4		
10	7	8		
7	5	3		
4	1	1		
6	1	1		
5	2	0		
6	3	3		
10	1	1		
4	5	5		
8	5	1		
2	2	2		
6	6	5		
4	6	1		
3	1	2		
9	5	8		
5	7	1		
7	3	8		
5	5	8		
5.77	3.88	3.44	Mean	
2.36	2.13	2.87	Stdev	
40%	54%	83%	Cosff. of Variation	
4	5	1	Mode	
2. Manmade, riprap, rubble and seawall				
Vulnerable to oil	Sensitive to oil	Cleanup		
1	2	3		
8	7	8		
7	1	4		
6	3	4		
1	2	2		
4	1	2		
5	4	2		
9	1	1		
7	3	2		
8	5	1		
1	1	1		
1	1	2		
6	3	1		
2	2	7		
7	4	7		
10	10	10		
2	7	8		
3	8	7		
4.88	3.61	4	Mean	
3.06	2.74	2.99	Stdev	
62%	75%	74%	Coeff. of Variation	
1	1	2	Mode	

3. Flat, dead seaweed and drifted wood beach				
Vulnerable to oil	Sensitive to oil	Cleanup		
6	6	8		
3	4	5		
6	1	10		
7	7	5		
9	7	7		
8	9	7		
8	10	9		
8	9	9		
5	3	1		
1	1	1		
3	3	3		
8	10	7		
7	2	8		
10	9	10		
10	10	7		
5	7	5		
2	3	3		
6.33	6.16	6.33	Mean	
2.67	3.34	2.86	Stdev	
42%	54%	45%	Coeff. of Variation	
8	10	7	Mode	
4. Narrow, sand barrier beach				
Vulnerable to oil	Sensitive to oil	Cleanup		
2	3	3		
8	5	5		
4	3	3		
3	5	3		
3	4	2		
6	7	3		
4	4	2		
8	5	9		
2	2	2		
5	3	2		
2	2	2		
4	3	4		
4	5	3		
8	6	7		
5	4	2		
1	6	1		
7	8	8		
3	6	5		
4.38	4.5	3.66	Mean	
2.22	1.68	2.27	Stdev	
50%	37%	62%	Coeff. of Variation	
4	3	2	Mode	

5. Flat, fine-to-medium-grained sand shore zone				
Vulnerable to oil	Sensitive to oil	Cleanup		
7	8	9		
9	4	5		
6	6	2		
6	4	6		
4	5	2		
5	5	5		
7	5	3		
9	5	9		
5	2	3		
5	3	1		
3	4	3		
6	7	5		
7	7	5		
5	5	5		
6	5	4		
1	5	1		
7	3	8		
4	6	4		
5.66	4.94	4.44	Mean	
1.97	1.51	2.43	Stdev	
34%	30%	54%	Coeff. of Variation	
7	5	5	Mode	
6. Flat, bedrock or beachrock shore zone				
Vulnerable to oil	Sensitive to oil	Cleanup		
8	9	4		
6	5	5		
9	9	2		
7	4	3		
7	6	3		
3	6	2		
6	7	5		
8	5	5		
6	2	2		
5	7	5		
2	2	2		
8	2	6		
6	8	4		
2	2	7		
5	9	0		
10	10	0		
5	7	8		
7	5	5		
6.11	5.83	3.77	Mean	
2.21	2.66	2.21	Stdev	
36%	45%	58%	Coeff. of Variation	
6	2	5	Mode	

7. Flat, compacted mud/silt intertidal shore zone					
Vulnerable to oil	Sensitive to oil	Cleanup			
3	5	6			
8	4	5			
7	7	6			
5	6	4			
6	6	2			
3	4	3			
4	6	6			
8	5	5			
5	5	5			
5	7	5			
1	2	1			
5	6	7			
5	4	2			
3	3	3			
4	7	0			
4	2	1			
5	3	8			
6	5	5			
4.83	4.83	4.11	Mean		
1.79	1.61	2.24	Stdev		
37%	33%	54%	Coeff. of Variation		
5	5	5	Mode		
8. Flat, silt/sand supratidal zone (sabkhah), could be oiled during high water level					
Vulnerable to oil	Sensitive to oil	Cleanup			
1	2	1			
2	3	3			
6	2	2			
8	3	1			
5	3	1			
1	3	3			
5	4	3			
9	6	6			
3	1	2			
5	7	5			
4	3	3			
9	4	3			
9	5	4			
6	7	5			
8	8	5			
5	3	1			
5	8	8			
7	6	8			
5.44	4.33	3.55	Mean		
2.59	2.16	2.22	Stdev		
47%	49%	62%	Coeff. of Variation		
5	3	3	Mode		

9. Sheltered lagoonal tidal flats				
Vulnerable to oil	Sensitive to oil	Cleanup		
9	10	10		
10	10	10		
10	10	10		
9	7	8		
4	7	6		
7	6	5		
4	10	9		
10	8	9		
1	10	5		
8	9	5		
2	9	10		
2	6	2		
9	9	4		
5	9	4		
3	10	3		
0	10	10		
2	8	7		
5.58	8.7	6.88	Mean	
3.57	1.44	2.8	Stdev	
63%	16%	40%	Coeff. of Variation	
9	10	10	Mode	
10. Sheltered salt marsh and mangrove				
Vulnerable to oil	Sensitive to oil	Cleanup		
10	10	10		
10	10	10		
8	9	9		
8	10	8		
7	8	8		
8	9	9		
9	10	10		
9	10	10		
10	9	10		
1	10	10		
10	10	10		
2	10	10		
4	10	5		
10	10	3		
10	10	8		
10	10	1		
0	10	10		
1	9	8		
7.05	9.66	8.27	Mean	
3.66	0.59	2.65	Stdev	
51%	6%	32%	Coeff. of Variation	
10	10	10	Mode	

11. Seagrass beds				
Vulnerable to oil	Sensitive to oil	Cleanup		
9	10	10		
9	8	6		
5	7	5		
7	6	5		
4	6	2		
7	8	7		
5	8	2		
9	10	10		
6	10	10		
5	10	10		
10	10	8		
10	10	10		
6	7	2		
10	10	3		
5	9	1		
3	5	1		
1	9	10		
1	10	9		
6.22	8.5	6.16	Mean	
2.9	1.68	3.58	Stdev	
46%	19%	58%	Coeff. of Variation	
5	10	10	Mode	
12. Coral rock beds				
Vulnerable to oil	Sensitive to oil	Cleanup		
10	10	6		
8	6	6		
10	10	6		
10	9	6		
9	9	9		
8	9	3		
9	9	5		
9	10	10		
2	10	7		
3	10	10		
10	10	9		
10	10	10		
7	8	2		
10	10	8		
10	10	0		
10	10	1		
1	9	10		
1	10	9		
7.61	9.38	6.5	Mean	
3.36	1.03	3.24	Stdev	
44%	10%	49%	Coeff. of Variation	
10	10	6	Mode	

13. Sand banks				
Vulnerable to oil	Sensitive to oil	Cleanup		
3	2	1		
4	4	3		
2	3	1		
7	8	4		
6	3	2		
6	5	2		
5	1	1		
0	0	0		
7	2	3		
8	1	1		
3	3	2		
10	10	10		
6	5	3		
4	4	2		
0	1	0		
1	1	1		
5	9	10		
7	7	8		
4.66	3.83	3	Mean	
2.78	2.97	3.12	Stdev	
59%	77%	104%	Coeff. of Variation	
7	1	1	Mode	

APPENDIX 2

AN OPERATIONAL SUMMARY OF THE APPROACH TO ESI ANALYSIS IN QATAR

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1. CONSERVATION OF THE COASTAL RESOURCES IN THE ARABIAN GULF

Since this thesis will be used by non-specialist professionals in Qatar, it is regarded as helpful to provide an integrated summary of the ESI technique that has been developed before providing a set of conclusions. Oil pollution in the Arabian Gulf is inevitable and coastal developments such as landfill, dredging, reclamation, and human predation of marine wildlife and eggs have increased the intense pressure on the marine and coastal environments of the region. Thus, coastal environmental management will not be effective if the local people in the Gulf do not realise the importance of the conservation of the coastal zone fragile habitats. In addition, ESI mapping will not be used unless they appreciate that the fragile coastal zone habitats in the Gulf will be damaged by oil spills. Moreover, they should realise that these habitats support a dense population of invertebrates and form the nutritional basis upon which the Arabian Gulf ecosystem depends, and provide the "international airports" for many migratory seabirds and marine animals. Any damage to these sensitive habitats will consequently degrade commercial fisheries in the whole Gulf and reduce the survival of many endangered animal species including those of global significance. Therefore, the development of a comprehensive public awareness programme in the Gulf region by using posters, audiovisuals and other materials, is essential to enhancing the coastal environment management in the Arabian Gulf region.

2. CONVENTIONAL SURVEY DATA USED IN THE ESI MAPPING

As has been demonstrated in Chapter 7, the conventional survey data used in ESI mapping were derived from the geologic and topographic maps of Qatar plus the available literature about the coastal zone in Qatar and field work. These maps provided the information needed for ESI mapping such as the coastal geomorphology and composition plus the location of the offshore reefs and sand banks. However, these maps were found to be lacking the most important information needed in the ESI mapping, namely the vegetated habitats of the coastal zone of northern Qatar such as the seagrass, mangrove, and salt marsh, which are the most critical during the oil spills. The maps were useful in providing the information on the location of the urban areas along the coast, jetties, and road network including the desert tracks which are needed when personnel in charge of cleanup operations must be dispatched to the shoreline.

Very few studies have been published on the coastal zone in Qatar that can be used in the ESI mapping of northern Qatar. The airborne remotely sensed data plus the field check were essential in providing the missing information on the coastal zone of northern Qatar. Detailed maps of the critical vegetated habitats were interpreted from the MEIS imagery and included in the ESI mapping.

3. THE AIRBORNE MEIS DATA USED IN THE ESI MAPPING

The airborne remotely sensed data used in the ESI mapping of northern Qatar coastal zone were made of rectangular mosaic blocks of MEIS data. Each mosaic was composed of five to seven portions of adjacent flight lines and, when geometrically corrected, covered an area of 5 km by 5 km. A large range of information can be obtained from these mosaics of MEIS data for the coastal zone in Qatar, not necessarily related to oil spills. However, generating the rectangular mosaics of MEIS data made the handling and analysis of these data by the computer unnecessarily difficult.

Generating the mosaic tiles made the size of the computer image file large and the image data were surrounded by a white area in order to finish the shape of the rectangular mosaic block. Many mosaic tiles covered only a small portion of the study area within the 5 km by 5 km area because the mosaics may extend beyond the data acquisition sector and were filled with pixels that were set to 255 (in the gray scale) in all eight MEIS channels. This affected the image processing analysis of the data, therefore a masking technique was first applied to the data before any further processing.

The mosaicking of adjacent flight lines introduced some artifacts in the analyses, as seen in the results of the supervised classification technique when using all eight bands of MEIS data, and also when using the automated spectral pixel unmixing analysis. This was due to the differences in the illumination intensity between the adjacent flight lines which had appeared in some of the MEIS bands. This confused the processing algorithm and produced some kind of wide parallel stripes in the final output results. It would possibly have been better if the MEIS flight lines had not been mosaicked, or if the mosaicking was only applied to the output results from processing these flight lines.

4. INTERPRETATION OF THE AIRBORNE MEIS DATA

As discussed in Chapter 5, four types of analyses were applied to the mosaicked airborne MEIS data. First was the image classification analysis (unsupervised and supervised techniques). The objective was to produce a land cover map of coastal zone habitats (vegetated habitats) suitable for exporting to the GIS system. No information was previously available about these coastal zone habitats in Qatar to support the classification, that was why unsupervised classification and field work were applied first in order to build an understanding about the distribution of the coastal zone habitats in northern Qatar. Then a supervised classification was applied based on the information collected from the field.

The result of the classification was affected by some "salt and pepper" appearance which affected the conversion process of the final classified map from the raster layer to the vector polygon layer in order to export it to the GIS system. The number of raster cells was greater than could be handled by the system. The vegetated habitats in the coastal zone of northern Qatar do not form homogeneous cover types but rather scattered types, where small bare gaps between plants are always present. Therefore, decreasing the size of the ground instantaneous field of view (GIFOV) of the MEIS sensor increased the number of classes that could be identified in the image, but at the same time increased the appearance of these bare gaps between the vegetated habitats and made the resulting image appear with some "salt and pepper" effects.

In addition, we are classifying a very complicated surface type (the coastal zone) where water will always be present. We cannot mask out the water because we are interested in mapping the habitats of the shallow water such as the seagrass in northern Qatar which is very sensitive to damage from the oil spills. This situation also introduced uncertainty into the automated classification.

The second analysis applied to the MEIS mosaicked data was resampling in order to reduce the size of the image file to more manageable size by the computer and then apply the same classification technique. However, the classification results from the resampled image (10 m pixel resolution) was rather noisy and showed more "salt and pepper" effects. This was due to the resampling technique, which caused a disjointed appearance in the output image products, and at the same time to the mosaicking technique which had been applied to the original flight lines of MEIS data. The size of the image was reduced to a manageable size by the computer, but at the same time we lost the benefit of having the data in 2 m spatial resolution to map the sparsely vegetated habitats in the coastal zone of northern Qatar.

The third image processing technique applied to the MEIS mosaicked data was image compression. Image compression was found necessary in an application where many large images were to be used, such as the airborne data set for the coastal zone of Qatar. Image compression reduced the actual size of the images and saved the output images in a compressed format that could easily be displayed and printed. This is usually done by removing the redundancy from the original images data by a compression algorithm. Image compression such as the JPEG algorithm worked very well for the mosaicked airborne MEIS data set. Detailed mapping was achieved for the areas which are very sensitive to oil spills such as the seagrass, salt marsh, mangrove, and intertidal area by using visual interpretation of the high quality compressed images.

Finally, automated spectral pixel unmixing analysis was applied to the airborne MEIS data to test the application of this technique to a large volume data set, and fully to automate the interpretation analysis, and at the same time to produce abundance images for each type of coastal zone vegetated habitat. The results of this could then be exported to the GIS system and used in the ESI of northern Qatar. Unfortunately, like most of the other analyses, the unmixing technique was badly affected by the mosaicking of the adjacent flight lines.

Pixel unmixing compressed the airborne MEIS data to separate the signal from much of the noise and then identified the smallest dimensions (3 dimensions) that adequately expressed the variability of the data. This reduced the computational time requirements for subsequent processing of the data. At the same time it overcame the problem of having a data set that was very large and covered large areas, because now we are only processing three bands of noise-free MEIS data. These three bands were used to extract the endmember spectra and build a spectral library of surface materials to be used for pixel unmixing and the production of abundance images for each type of surface material.

However, most of the abundance images were highly affected by the mosaicking that had been applied to the adjacent flight lines of the MEIS data. It was concluded that the resulting abundance images of the coastal zone vegetated habitats would have been better if the MEIS data had not been mosaicked. For future application of remote sensing for this purpose in Qatar, it is recommended that a spectral library of surface materials should be generated using linear spectral unmixing and field spectroscopy to unmix the surface materials and produce abundance images for each type. This will overcome the problem of always having mixed pixels in the final classification, and at the same time it will enhance the classification process of the remotely sensed data.

5. THE PROPOSED ESI FOR THE NORTHERN QATAR COASTAL ZONE

As was discussed in Chapter 6, the ESI developed for the coastal zone of northern Qatar used conventional survey data and high spatial resolution airborne MEIS data. The development of the ESI, in addition, was based on known interactions of oil with various coastal types which have been observed over the past years. The main diagnostic attributes which influenced the ESI were coastal form and sediment type, shoreline interaction with the oil, oil persistence in that environment, and the extent of biological damage. It was impossible to include more biological attributes, such as the migration of marine mammals and birds (for example: indicating areas critical to these species for reproduction, feeding, and the seasons in which these species use certain areas) in the proposed index, because this information is not available in Qatar. In addition, such information must be collected by knowledgeable biologists and marine scientists. If this information was available, it might alter the sensitivity of the proposed ESI classes. Different indices may form according to the seasons in which these species use certain areas of the coastal zone.

Airborne MEIS imagery was used to integrate some biological features into the ESI such as the vegetated habitats. Three types of vegetated habitats were classified in the shallow water and fragile intertidal zone for the first time in Qatar using the MEIS imagery. These habitats were seagrass beds, salt marshes, and scattered mangrove forests. They received the highest sensitivity ranking in the proposed ESI for their high biological value and the extent of potential biological damage.

During the field work, the sensitive salt marshes were found to be a breeding and resting area for a large number of two types of water birds (*Socotra cormorant* and *Kentish plover*). The seagrass beds were found to be a feeding area for the most popular fish in Qatar (*Siganus canaliculatus*). The muddy sediment of the mangrove forests were colonised by a very large number of crabs.

To elicit opinions on the ESI ranking of the various coastal zone types, the proposed ESI was discussed with the local experts in Qatar. The local experts seemed to have a good understanding of the value of biological features such as salt marsh and mangrove, and the impact of oil on these sensitive environments. However, they did not understand the interaction of oil with each type of the coastal environment. Local training is very important and needed in order to have better planning and response for combating the oil spills. This can be achieved by applying short training courses in oil spill response for the people that are responsible for the protection of the marine and coastal environments in Qatar. Testing the proposed ESI for northern Qatar is also essential and can be done during the training courses.

6. THE GIS ESI MAP OF NORTHERN QATAR

The traditional approach in handling ESI information was in hardcopy form and manipulating it through manual techniques. Given the difficulty of applying consistent procedures within such an approach, GIS is now used to support oil spill response planning. As discussed in Chapter 7, the ESI information compiled for the northern Qatar coastal zone was manipulated through the SPANS GIS system and the GIS ESI map for northern Qatar was produced. This map provides guidance for oil spill response and planning in Qatar and at the same time gives access to information for the personnel in charge of cleanup operations.

The map highlighted the most sensitive areas along the coastal zone of northern Qatar with the shoreline access and the areas that are known to be important for seabirds and fisheries depicted by symbols on the map. The map remains in digital form which can be updated any time when new information about the coastal zone sensitivity becomes available. For instance, if information on the seasons in which the species use certain areas were available in Qatar during the time of an oil spill, an ESI map with the appropriate season could be produced for the personnel in charge of cleanup operations to facilitate their tasks.

In conclusion, the present ESI mapping of northern Qatar coastal zone using remote sensing and GIS systems provides a system and a base for the protection of the coastal zone environment in Qatar. Still more information on the vegetated habitats can be extracted from the remotely sensed data for the rest of the coastal zone which then can be added to the GIS database. In addition, information on the oil sensitive wildlife can be added to the database. Such a task can be carried out as a national survey along the whole Qatari coastal zone.

7. ACTION PLAN FOR USING REMOTELY SENSED DATA AND GIS IN OIL SPILL RESPONSE

Oil spills will continue to occur in the Arabian Gulf as long as we develop and use these valuable petroleum resources. Therefore, we must be prepared to respond to the inevitable spill. As it has been discussed and demonstrated throughout this thesis that remote sensing and GIS technologies will remain a vital part of that response. In addition, as it has been developed throughout this thesis, now the quickest way for mapping shoreline characteristics for ESI operational response involves the usage of fine spatial resolution remotely sensed data such as the airborne MEIS coverage of the whole coastal zone of Qatar. This airborne MEIS coverage consists of an archive of 233 mosaic tiles, each is covering an area of 5 km x 5 km of the coastal zone, which have been used to provide the necessary information for combating the oil spill. However, managing such large volume of archived data is not simple especially in an oil spill operational response, when time is considered to be an important factor that must be taken into consideration for the movement of an oil spill.

Airborne MEIS system has provided Qatar with a unique remotely sensed data set from which coastal resources could be mapped in detail, therefore increasing the reliability and efficiency of the oil spill impact modelisation. However, generating the MEIS data set has been effected by two problems, mosaicking and blurring. Generating the rectangular mosaic tiles of MEIS data made the image affected by flight lines that run parallel to each other with variation in their illumination intensity (see Chapter 5: Figure 5.7). This effect introduces more noise to the automated classification applied to the data. Such effect might be corrected but with lost of effort.

In addition, generating the mosaic tiles increased more the volume of the data set than what was acquired during the scanning operation. Many mosaic tiles were found covering only a small portion of the actual image data surrounded by white areas in order to finish the shape of the rectangular mosaic tile (see Chapter 5: Figure 5.6). Finally, the data set was found affected by blurring, which was introduced by the sensor during the scanning operation (see Chapter 5: Figure 5.8).

Therefore, the best route which has been developed using the archived MEIS data set for the ESI operational response is shown in Figure 1, where image compression is found to be necessary in application when many large images are to be used such as the archived MEIS data set. By applying the image compression, it reduces the actual size of the images and saves the output images in compression format that can be easily displayed and/or printed in high quality hardcopy images. This is done by removing redundancy from the original images data by mapping the images to a set of coefficients then quantized the resulting set to a number of possible values. These values are then encoded by a suitable coding method.

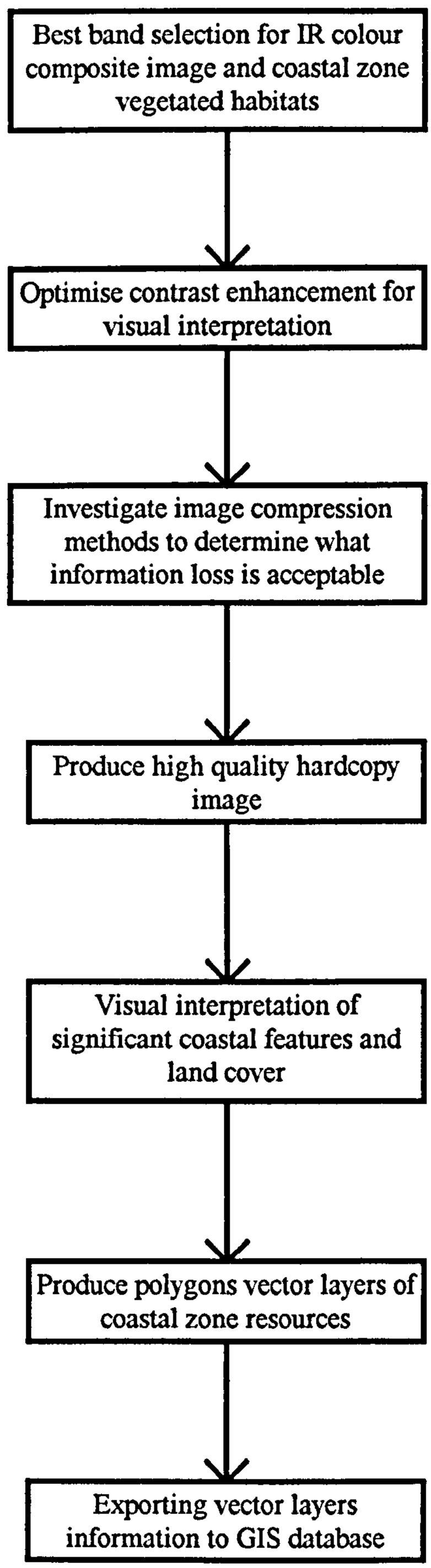

Figure 1 The best route developed using the archived MEIS data set for ESI operational response.

The production of the high quality compressed images and the climatic and environmental conditions in the Arabian Gulf made the visual interpretation and mapping of significant coastal zone features and land cover more possible. Very detailed maps of the sensitive coastal resources were visually interpreted from the compressed MEIS images. Impacted areas with oil tar from the last oil spills in the Gulf in January 1991 were also mapped. The JPEG image compression algorithm was very useful for manipulating the large archived MEIS data covering the coastal zone of Qatar. Such analysis can be applied in any part of the Arabian Gulf especially with new generation of the satellite sensors where the fine spatial resolution is a common feature.

Airborne remotely sensed data cannot be acquired in repetition coverage in the Gulf region such as the satellite programme for example to study a continuous processes or phenomena in the coastal zone. Neither Qatar nor any other country in the Gulf has the facilities for acquiring a new airborne data. Any new acquisition has to come from hired foreign airborne sensors which might add some expenses to the already expensive airborne data. However, in the next decade a new fine spatial resolution satellite sensors will be available to supply the world with very high spatial resolution imagery. Images as fine as 1 m spatial resolution in panchromatic mode and 4 m in multispectral mode will be available widely for the earth surface (see Chapter 2: Table 2.3).

Thus what type of coverage: for example, full coverage for the whole of Qatar or the whole of the coastal zone or just for selected areas of fine spatial resolution of satellite imagery would be needed in the future for Qatar and for what purposes? The experienced gained from manipulating the large volume of archive airborne MEIS data for the whole coastal zone of Qatar explained that there is no need to have a full coverage from the future fine satellite imagery and keep having large archives of remotely sensed data in Qatar. Such fine satellite imagery would be useful for selected areas, however, the cost of such data is still unknown. The question is which areas in Qatar would need such fine spatial resolution of remotely sensed data and why?

First, fine spatial resolution satellite imagery will be needed in Qatar to study the impact on the coastal zone from proposed developments in order to reduce the degradation of marine environment in the Gulf to its minimum. The development has become concentrated along its coast where landfill, dredging and reclamation activities have conducted systematically on a large scale and thus fine imagery effective environmental management. Second, fine satellite imagery will be needed for mapping and monitoring programme of the sensitive habitats along the coastal zone. Coral reefs with their associated islands, seagrass beds, mangroves, and intertidal salt marshes are the most critical habitats in the Gulf. Biologically they are the most productive habitats in the region. The supply the energy needed to sustain the marine life in the Gulf and provide breeding sites for many endangered animal marine species.

Therefore, fine satellite imagery will remain a vital part for the preservation of these habitats in the Gulf. In addition, fine satellite imagery will also be a vital part for monitoring the industrial areas along the coast and the shipping oil terminals in the Gulf such as Halul island, northeastern Qatar. Figure 2 shows the proposed selected areas for the new fine spatial resolution satellite imagery, and such coverage of selected areas can also be applied elsewhere in the Arabian Gulf region.

The use of fine spatial resolution remotely sensed data and GIS for ESI mapping and operational response can be divided into two modes. First is the generation of the ESI maps using remote sensing and GIS systems (passive mode). Second is the use of these ESI maps and other related information in the operational response of an oil spill incident (responsive mode).

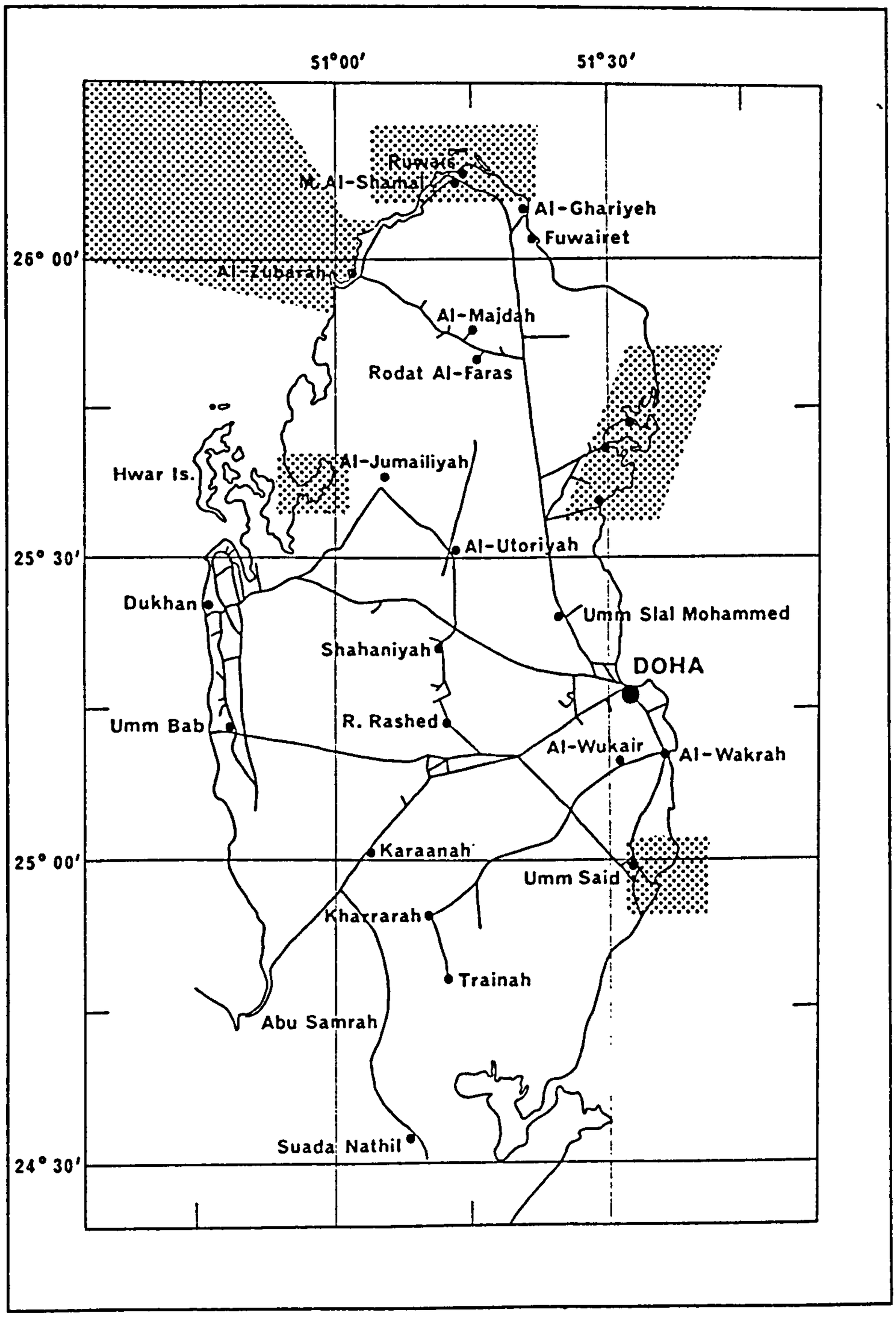

Figure 2 The proposed areas in Qatar for the coverage by the new fine spatial resolution satellite data.

In the passive mode, the task is involved first in the extraction of MEIS raw data from the archive types and import it into ENVI software package for the JPEG compression. Such operation will need one day for 12 of the MEIS tiles each covers an area of 5 km x 5 km. Once the images are in a JPEG compression format, the next task is importing these compressed images into Photoshop software package in order to produce a high quality image that show in detail shoreline characteristics by using a colour laser printer. Visual interpretation should be applied to the hardcopy of the compressed images by experienced geologist to produce a categorised maps that show the various types of environment present in that part of the coastal zone. The interpreted map should be reclassified according to the interaction of each type of environment with oil, oil persistence in that environment and the extent of biological damage.

In other words, the maps should be reclassified according to the developed ESI for that part of the coastal zone region. A colour ESI maps would be produced to show the coastal environmental sensitivity with respect to oil spill impact. Two to three days will be needed to import the 12 compressed images into the Photoshop software package, produce the hardcopy of the compressed images and the final ESI colour maps. In addition, two to three days also will be needed for a field check and verification of the interpretation results.

ESI maps should be accompanied with coastal zone wildlife information and shoreline access. Digital database of all these information should be built with continuous updating process. GIS should be used to produce the ESI maps and to applying rapid and consistent procedures within such an approach to support contingency or operational response to oil spill.

For the future fine spatial resolution satellite imagery, the same process discussed above of using JPEG compression and visual interpretation can be applied, once the needed fine spatial resolution image tiles are identified and geocoded. Moreover, automated analysis such as spectral pixel unmixing could also be applied to the fine satellite imagery. Such analysis is a potential area for future study and the procedure developed in this thesis for using spectral pixel unmixing to unmix MEIS data could be an extremely useful prototype. Abundance images of surface material and coastal zone habitats could be produced using pixel unmixing. These images could be used in the ESI mapping and coastal zone GIS database.

In the operational responsive mode, once an oil spill occur in the Gulf, the location and size of the spill should be known using for example a spotter plane with video or film camera. Information on the winds and currents direction should be estimated for example at least a week ahead in order to predict the movement direction of the spill in the Gulf. Oil spill prediction model could be used to predict the movement of the spill by feeding the model with the information collected in the location of the spill and the direction of the winds and currents of the region. Radar satellite imagery, in addition, could be acquired for larger spills, however, data delivery time is a problem.

At the same time GIS should be used to support the oil spill response planning. GIS should be used to produce the ESI maps accompanied with the information on wildlife and shoreline access for the section of the coastal zone that under the threat of being polluted by the spill. All these information with the compressed images should be given to the cleanup operation crews to provide the necessary protection for the most sensitive areas of that section of the coastal zone. Crews must be dispatched to the various shorelines using the information provided by the GIS for example the road network including desert tracks, jetties and coastal town and villages.

All this information is of critical importance in oil spill planning especially when crews must be dispatched to the various shorelines for the initial placement of booms and oil skimmers to prevent oil from reaching the sensitive section of the coastal zone. Finally GIS should be used to provide the necessary information such as coloured maps and images for the media and public awareness.

8. THE MANAGEMENT CONTEXT FOR ESI ANALYSIS IN QATAR

The methods used in this thesis for producing high spatial resolution land cover maps of the coastline of Qatar using remote sensing and GIS, and identifying the most appropriate methodology for use in an operational coastal zone management system, should be very useful and important especially to the Environment Department, Ministry of Municipal Affairs and Agriculture. The reason for this proposal is that the Environment Department with its Environmental Protection Committee are the responsible agencies in Qatar to deal with the appropriate measures to combat environmental disasters especially oil spillage. The Director of the Environment Department is at the same time the Secretary General of the Environmental Protection Committee which has been established by the government of Qatar subject to major disasters in the 1980's. The membership in the Environmental Protection Committee is from cross-sectoral departments in the State and its objectives were developed as follows:

- Protecting the Qatar coastline from indiscriminate oil dumping and oil spillage.
- Combating ecological dangerous spillage adjacent to the coastline of Qatar.
- Mounting cleanup and rescue operations to Flora and coastline Fauna.
- Provide environmentally safe disposal of oil refuse arising from cleanup operations.

It can be seen that the remit of the Committee is currently reactive rather than proactive. As it appears from the objectives of the Environment Department, production of high spatial resolution land cover maps of the coastal zone of Qatar is not included, nor has the Department the facilities and expertise for such task. The production of such maps should be done in fact at the Scientific and Applied Research Centre (SARC), University of Qatar, since SARC is the only agency in Qatar that has the capability of remote sensing and is the site where the present airborne MEIS data are stored. However, SARC in the meantime still needs further to develop its facilities in remote sensing from PC-based work stations with limited storage capability to more advance work station that can handle both remote sensing and GIS analyses plus the large volume of remotely sensed data. For example, hardware such Unix-based with large storage capability is needed and software such as ERDAS Imagine, ENVI, and SPANS.

In addition, SARC should develop a comprehensive programme for the collection of oil spilled wildlife data, and be in a position to provide a new remote sensing capability when needed for the updating of the ESI maps, establish a comprehensive data base for the coastal zone of Qatar, produce the ESI maps for the people in the Environment Department that are responsible for the protection of the coastal zone environment and finally provide short training courses in oil spill response to the same people in order to have better planning and response for combating the oil spills in the Gulf. Figure 3 illustrates an oil spills plan for Qatar that can be developed by SARC and the Environment Department.

The structure suggested retains the responsibility and authority of the Environment Department and Committee structure, but adds a new layer of technical capability. It also takes the important and fundamental step of moving from a reactive stance to a proactive approach.

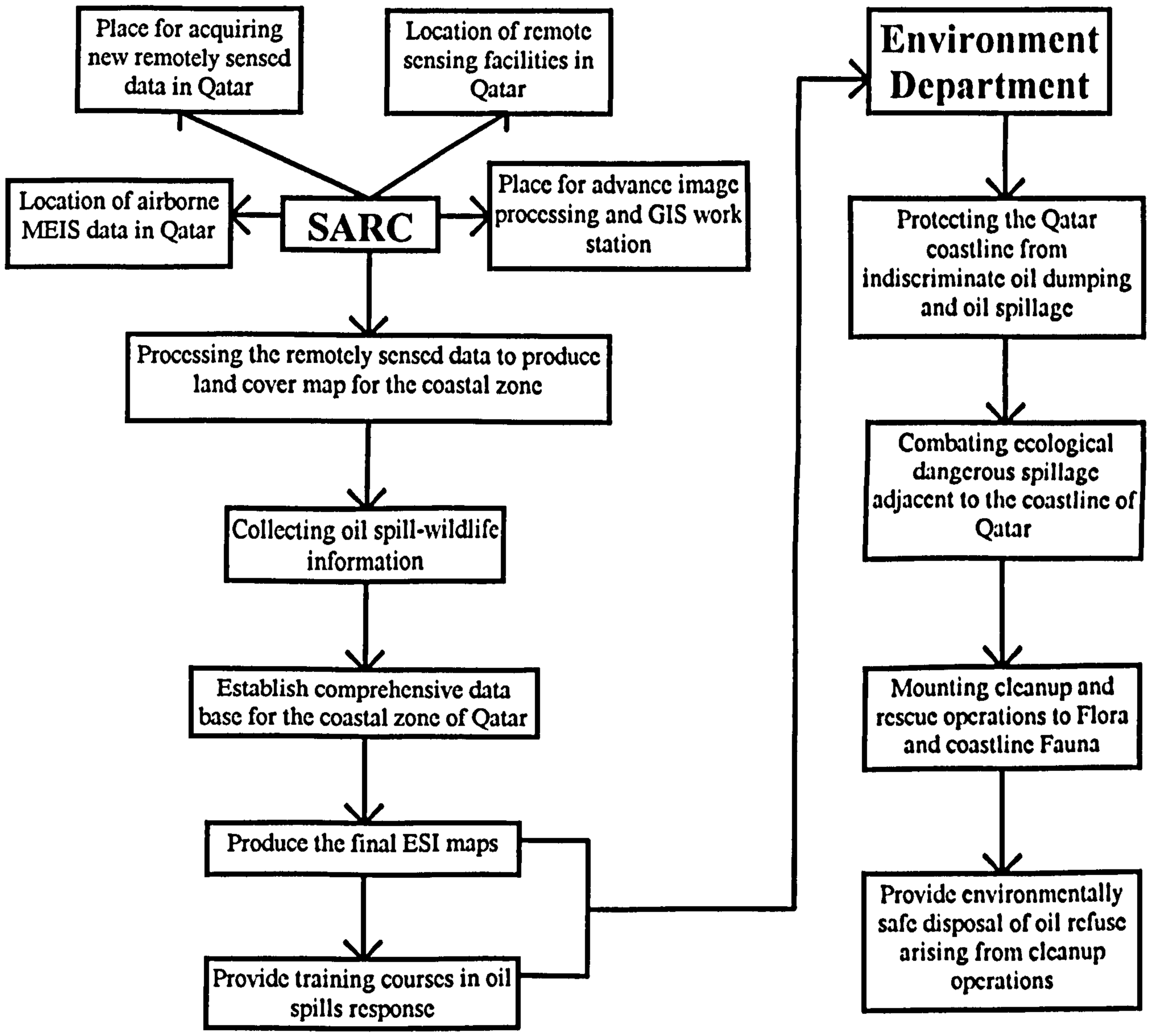

Figure 3 Oil spills response plan for Qatar.