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USE OF REMOTE SENSING TO DETERMINE POLLUTION FACTORS, LOCATION AND DYNAMICS ON THE LEBANESE LITTORAL

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The littoral of Lebanon has been impacted by several pollutants whose source is the terrestrial environment and human activities. The two major pollutants are detritus and organic materials. The detritus spreads over a large areal extent and consists mainly of sediments and debris from watercourses. Organic pollutants are mainly wastewater and oily and chemical residues. The factors influencing the spread of these materials into the sea were studied, including the physiography, landcover/use, and hydrography of the terrain. Remotely sensed data was used for the study. Major pollution sources appear as distinct optical features and 34 are identified along the littoral, Field verification confirmed the satellite imagery information. Detritus and wastewater appear to directly flow into the sea and are often derived from sources at remote distances inland. Oil and chemical products appear to have a more diffusive flow behavior. Dynamic changes are much exaggerated in the case of wastewater and oil and chemical products.

INTRODUCTION

Direct and indirect dumping of liquid and solid waste materials into the sea along the Lebanese littoral has become a normal means of waste disposal. This, in turn, has led to the creation of several pollution sources along the Lebanese coastline (CNRS, 2007). These sources take on a miscellany of aspects and scales and are distributed all along the shoreline, and are most dense in the middle part where human activities are concentrated. The interaction between dumping wastes and seawater creates human health problems. Rarely a year goes by in Lebanon without a disastrous event resulting from seawater pollution.

Many studies have been conducted to assess marine water quality in Lebanon (Kouyoumjian, 1970; Harakeh, 1978; and Kayal, 1981). Most of these studies focussed on specific areas along the coast. However, after the issue of marine pollution became more important as a result of severe impacts on human health and the environment, more detailed studies have been conducted (Yezbek, 1990; Greenpeace, 1997; Chatila, 2000; CEDRE, 2002; Khalaf, 2004; Nassif, 2004; and Nakhleh, 2004).

The coastline of Lebanon lies along a mountainous region with a large number of pollution transport paths. These are either natural drainages (rivers and streams), or man-made (sewers, outfalls, refuse tips, etc.). They transport polluted water as well as a sediments and debris from different sources, sometimes from remote distances from the sea (i.e. several kilometers). In addition, the coastline is characterized by steep sloping terrain that increases the energy of flow along these paths, and large amounts of materials can be carried into the sea.

Apart from the type and amount of wastes, there exist differences in the mechanisms of waste release into the sea from one region to another. This reflects the diversity in terrain characteristics, which influence the behavior and dynamics of pollutant transport. To assess these characteristics, remote sensing applications are useful since terrain properties are needed to obtain a spatial view. In addition, remotely sensed data types can be combined to create a monitoring approach to assess pollution dynamics, especially when sequential satellite images are available. Similar applications based on remote sensing techniques have been conducted to study the marine environment of Lebanon (Faour and Shaban, 2002; Nassif, 2004; and CNRS, 2007). This study is based on the most applicable satellite images of Landsat 7 ETM+, which provide a very precise 30 m resolution, and on up-to-date software for interpretation of the selected images.

The study area includes the coastal stretch that extends between Beirut and Tripoli, which is about 80 km in length (Figure 1). This stretch, and its adjacent land region, is well known as the most sensitive coastal zone in Lebanon since it includes the capital Beirut and its surrounding suburbs. The surveyed coastline extends along the Mediterranean Sea and is oriented in a NE-SW direction.

This study aims to assess the major factors influencing the behavior of marine pollution, notably the transport and dynamics of pollutant travel from the land to the sea, and the interaction between the land and the sea.

MATERIALS AND METHOD

This study was conducted in several phases. These were the analysis of satellite images as a first phase followed by field verification. The availability of satellite images for different periods of time provided the opportunity for a monitoring approach. The dynamic changes in pollutant behavior in space and time were examined to ensure the consistency of the identified pollution sources. The phases are summarized in Table 1.

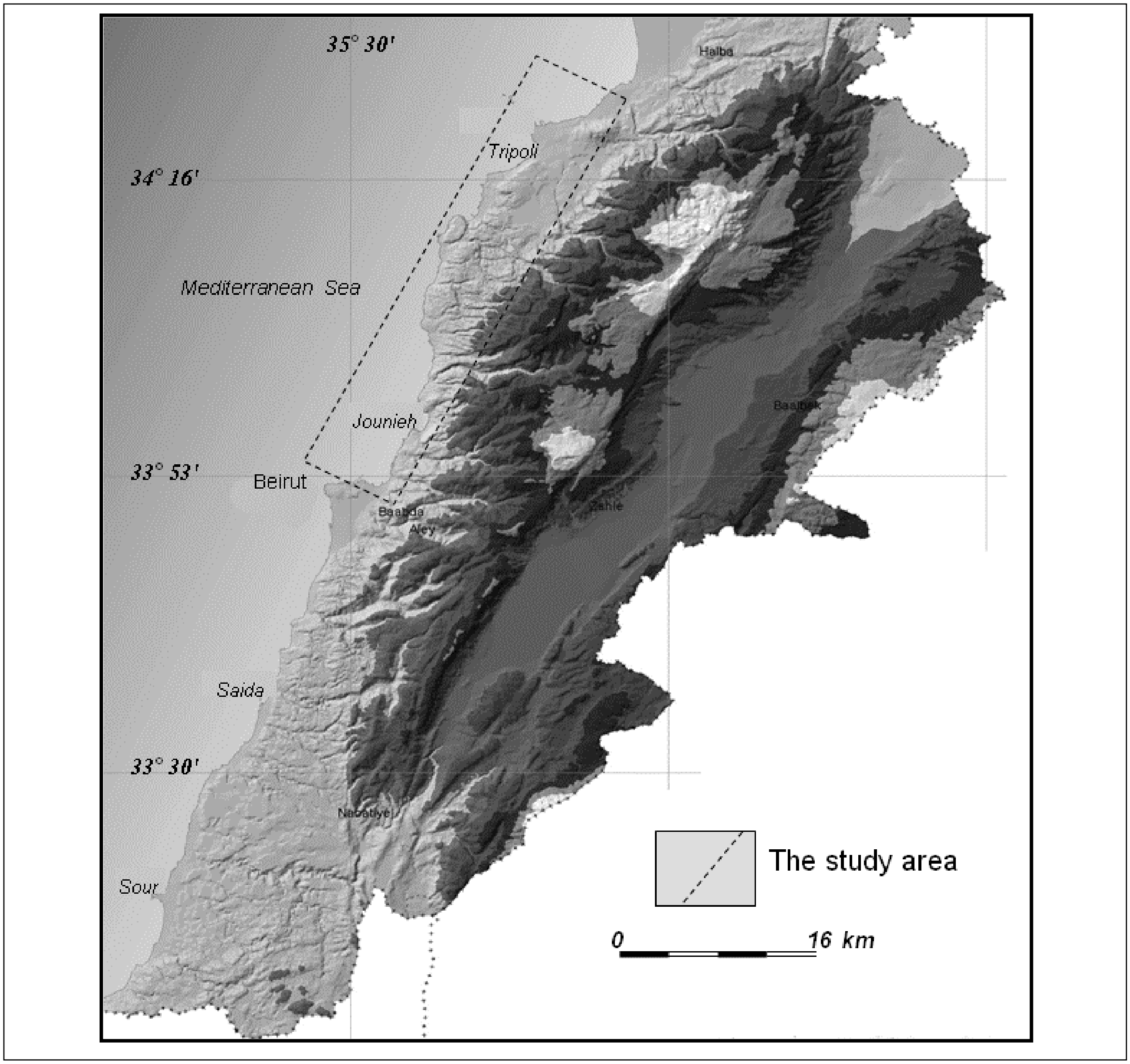

Figure 1. Location map of the study area.

The Landsat 7 ETM+ satellite images will have a unique and essential role in the realm of earth observing satellites in orbit by the end of this decade. No other system will match Landsat's combination of synoptic coverage, high spatial resolution, spectral range and radiometric calibration.

A Landsat image, with a repeat time of 16 days and swath width of a 185 km x 185 km, has eight spectral bands, in which bands 1-5 and 7 have 30 m resolution and wavelength range from 0.45 to 1.75 µm. While band 6 is thermal and has a special spectral resolution of 60 m and wavelength ranges from 10.4 to 12.5 µm, the last one, band 8 is panchromatic with 15 m spatial resolution and wavelength from 0.52 to 0.90 µm.

The images used in this study are from the years 2000, 2001, 2002 and 2003, with different time periods including wet and dry seasons. In addition, a Landsat image was merged with IRS-1 images (5.8 m x 5.8 m). In this procedure, we combined the color of the Landsat ETM with the higher resolution of the IRS-1. ERDAS Imagine and ENVI-4.3 software was used for image processing. This enabled us to discriminate features on the image associated with pollution sources.

Table 1. Phases and tools in the study.

Phase	Satellite mages analysis	Desk study & analysis	Field survey	Chemical analysis	Data interpretation
Tools	Landsat 7 ETM+ & IRC-1	Exogenetic data: topographic, geologic and Land cover/use maps	Field tools (GPS, STD Probe, etc)	Laboratory kits and tools	Complementary analysis and interpretation data
Output	Remarkable signatures into seawater and on terrestrial environment	Comparative and correlated elements between marine and terrestrial environments	Verification and confirmation of analyzed images	Quality control and assessment	Identifying major factors that control transportation of pollutants into the sea

All digital image data selected for the detailed spatial database required several preprocessing steps. These commonly consist of atmospheric correction or normalization, image registration, geometric correction, and masking geo-referencing. These processes must be applied to increase the accuracy and interpretability of the digital data during the image processing phase.

Selection of software depends on the resultant precision of features that exist on the processed image. Therefore, in many instances, we utilized several methods to process the same image.

After applying the different digital procedures, identification of marine pollutants depended mainly on the visible contrast among the most distinguishable elements of identification. These are: color, tone, texture, and flow pattern and temperature differentiation. These elements generalize pollutant type and behavior (CNRS, 2007). The observations from the satellite imagery should be accompanied with field verification in real time to confirm the image analysis results. In addition, the type of digital application applied to satellite images as well as the image characteristics themselves have a great importance.

Image analysis was carried out using ERDAS Imagine software, and in some instances ENVI-4.3 was utilized. The major steps began with satellite data preprocessing procedures followed by image sub-setting to identify the area of concern within the image. The limit of the study area was prepared in vector format to facilitate sub-setting of the image using Imagine software. This also had the advantage of creating smaller data sets for more rapid image processing on the computer.

The majority of analysis included applying special features in the software, notably, directional filtering, contrasting and sharpness. In addition, single band and multiband enhancements were carried out by interrelating each three bands as one set. These applications provided information to detect color differences, pattern and texture, which would discriminate distinguished features in the marine environment. Moreover, thermal interpretation from the thermal band 6 was undertaken.

As a second phase of study, the identified pollution sources were verified in the field to confirm the reliability of image analysis. This was undertaken using GPS (Global Positioning System) in addition to topographic, geologic and land cover/use maps. Topographic and geologic maps could help identify the surface and subsurface paths along which pollutants are transported. The land cover/use maps helped identify natural and human inputs and their location with respect to the pollution sources. These efforts complemented the satellite image analysis.

In the marine environment, and in addition to the above tools mentioned above, a STD (Salinity-Temperature-Depth) Probe was used to measure the salinity and temperature differences and thus confirm the information extracted from remotely sensed data. Moreover, sampling on selected sites was carried out for chemical/bacterial analysis. This analysis verified the water quality, and could distinguish water sources, whether from sewers or freshwater seeps.

Parallel to these phases, a desk study and data interpretation were carried out after the data collection and pollution source identification. Comparative analysis of data over different periods of time, correlation approaches between terrestrial and marine environments, and quality control of pollutants were obtained.

RESULTS AND DISCUSSION

The different components of marine pollution for the area of study is a result of direct and indirect disposal and release of wastes of widely varying types and behaviors. In general they are either due to the poor land use practices or to waste disposal from domestic urban, and industrial sources.

It is obvious that natural surface drains whether they are temporary (streams and wadis) or permanent (rivers) can be easily identified since they are observable. This is the case also for the man-made drains (sewers, refuse tips, etc). Hidden drains and paths can also exist in the area of concern such as fracture systems, rock faults and karstic conduits. There is also direct dumping, like landfills, direct outfall of sewers and other wastes. The factors influencing transport of these pollutants is largely governed by the terrain.

Physiography

The area of study constitutes a mountainous region that lies parallel to the shoreline. Tripoli, the second largest Lebanese city, borders the area of study on the north with the capital Beirut at the south. The coastal plain, a flat, cultivated area, is relatively narrow (<3 km width). The mountainous region has a maximum width of about 45 km and an average elevation of 1000 m and reaches about 3000 m in some places. The relatively narrow width of the area with steep sloping land results in acute slopes. Mountainous relief represents about 90% of the area of interest.

The distribution of elevated lands, from north to south is as follows: Kornet el-Aarouba (2223 m), Jabal El-Makmel (3000 m), Kornet Es-Saouda (3083 m), Jabal El-Mnaitra (2702 m), Jabal Sannine (2628 m), and Jabal El-Knaisseh (2091 m). The slope gradient ranges between 55-75 m/km in the south and 125-150 m/km in the north, thus averaging about 90-100 m/km, which is considered an acute slope gradient.

A miscellany of geological exposures exists in the studied area (Dubertert 1953, 1955; Ponikarov, 1967; and Beydoun, 1972, 1988). The stratigraphic sequence is typical for that of Lebanon, exposing rock formations from the Middle Jurassic to Recent. Carbonates are the most dominant rock type. They have different lithologic character and cover about 70% of the area. In addition, sandstones, shales, marls and volcanic rocks are exposed. The Litani watershed has fifteen rock formations interrupted by basaltic rocks, which often belong to the Pliocene age. The superposition of these rock formations is governed by many structural controls; notably faults, fracture systems and folds. Faults represent subsurface transport paths in some places and infiltrated pollutants can migrate along these faults.

Land cover/use

Land cover/use is another major factor affecting marine pollution, especially if located close to the coast. Land cover generally represents the natural components of the terrain, while land use includes the human activities on this terrain.

Usually land cover/use maps are obtained using satellite imagery that is capable of classifying and analyzing land components. In this study, obtaining a land cover/use map was based on a Supervised Classification of satellite images of two types. The merging of Landsat 7 ETM^+ (2000) pan sharpen and IRS-1 was carried out and a visual discrimination was based on optical differences thereby obtaining several polygons. Field verification was carried out to verify different units of land cover/land use in these polygons.

The classification has resulted six major classes (Figure 2). These are: horticulture areas and fruit trees (11%), urban settlement (7.5%), unimproved lands (26%), grazing lands (31%), bare lands (24 %) and water bodies (0.5%). Urban settlements are the most influential factors, since human activities produce the most abundant and harmful wastes.

There are other components of the terrain that can contribute in marine pollution, notably if they are magnified by human activity and climatic conditions. For example excavation sites, which produce erodible surface materials, can produce considerable pollution during heavy rains.

Hydrography

Western Lebanon as a whole is characterized by high precipitation. There are between 60 and 70 rain days per year (Atlas Climatique du Liban, 1982). The average precipitation is about 910 mm near Tripoli and reaches 870 mm near Beirut, thus averaging 640 mm.

The area of study encompasses a large number of watercourses. This is a result of heavy rainfall plus the steep sloping terrain, as well as rock faults that extend from land to sea. Six major (permanent) watercourses drain major catchments. These are from south to north: (1) Nahr Beyrouth, (2) Nahr Antélias, (3) Nahr El Kelb, (4) Nahr Ibrahim, (5) Nahr El-Jaouz, and (6) Nahr Abou Ali. The drainage system in this region is characterized by high density and dendritic patterns. The permanent watercourses are associated with several human settlements, which dump solid and liquid wastes into these courses. In addition, there are twice as many temporary watercourses which flow for a couple of months during the year. Both types of watercourses are known to carry big sediment loads, especially those of the permanent type. They can carry sediments several kilometers into the sea (Shaban et al., 2007). Erosion processes are enhanced in the area of study by several exposures of soft materials such as sandstone, clays and marls. Industrial sites along the watercourses contribute to the problem of marine pollution. These sites are often located close to the coastline.

The coastal stretch between Beirut and Jounieh was found to be the most sensitive region with regard to pollutant transport. This can be attributed to many factors including:

- The curvature in the coastline
- The steep slope gradient, which exceeds 125m/km
- The dense population size with several human activities
- The presence of several watercourses

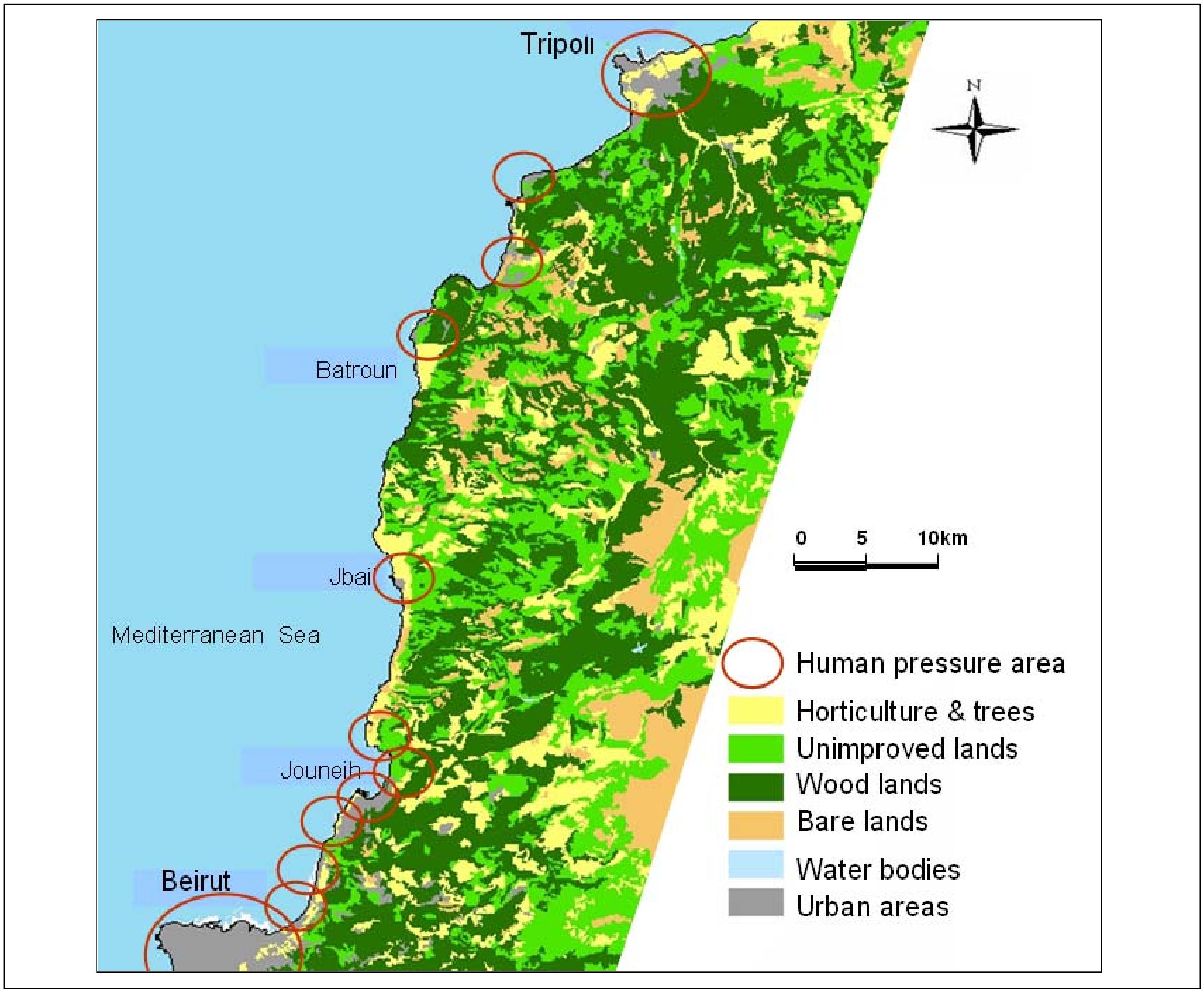

Figure 2. Land cover/use map obtained from Landsat ETM and IRS-1 Images.

The coastal stretch between Jounieh and Nahr Abou Ali in the north, including Naher Ibrahim and Nahr Asfour, has fewer pollutant sources. Nevertheless, it shows a high production of sediments and debris, notably in wet seasons. In some localities, there are sensitive sites along dense urban settlements, like Jbeil, Btroun, and Fidar.

Transport of detrital and soluble materials

The physiography, land cover/use and hydrographic characteristics of the study area adapt it to the production of detrital materials of different types and at different scales. This is enhanced by the effect of the steep slope and the existence of soft rock materials and soil deposits. These materials feed the marine environment with a miscellany of minerals or organic components that appear as sediments and rock debris. When these reach the sea, they are influenced by currents and wind velocity and direction. The degree of impact from these materials depends on if they are eroded slowly or if they are produced by some sudden event. The route along which the sediments and debris are transported plays an important role. For example if a watercourse has several meanders, this can reduce the amount of these sediments and vice versa. This is also the case for the steepness of channel slope.

For the soluble materials, the mechanism of transport is different. Most of soluble materials have originated from industrial activities/or wastewater discharges. They are represented by organic or bacteriological fractions (Nassif, 2004). Likewise for the fine mineral particles that are released by mining, such as those from cement factories along the coast. They also include organic compounds, which can result from uncontrolled releases from the drains from hygiene systems, wood wastes, plastics, fabric wastes, hospital wastes, and other sources.

Remotely sensed data can identify detrital materials as well as measure their areal extent in the marine environment. This information can be also be obtained by using low resolution satellite images (e.g. MODIS, AVHRR, NOAA, etc.). The precision of detrital material detection depends on the particle size of the suspended sediments. The larger the size of particles, the more precise the identification, whereas very fine fractions and soluble materials are more difficult to distinguish. The exception is oils and chemical products, where color and brightness can be seen.

Detecting transported materials to the sea is based on absorption and reflectance properties. This is closely related to the spectral signature and wave length of these features in the image scene. These materials can be observed and their dimensions can be obtained, and sequential images allow monitoring dynamic changes in time. Figure 3 shows an example of image use identifying detrital materials in the sea. In this case, the Landsat 7 ETM+ band combination is important, especially the order of bands 4, 2, and 3.

Localization of pollution sources

Remotely sensed data can be used to identify marine pollution sources with wide spatial coverage. This procedure can be a prerequisite for further field investigation and the application of image analysis can focus and expose anomalous sites in the marine environment. These sites show discriminated features in the images and they definitely reflect the existence of materials that have different pictorial properties than that of the seawater.

All elements of discrimination were utilized in this study in order to identify anomalous sites including color, tone, texture, and flow pattern and temperature differentiation. Just identifying these anomalous is not adequate to identify the material type and origin. Field verification must be carried out using different tools, to determine if the anomaly is due to pollution.

Figure 4 shows an example of pollution sources, which appear primarily as anomalous signatures on satellite images. It shows different digital applications of the same image scene, and displays features with a miscellany of optical characteristics. Identified sites were verified in the field and the dimensions were measured for each site using the measuring tool toolbar available in the software.

Figure 5 shows a general identification before a more precise analysis takes place to focus on detailed signatures in the analyzed image. It is based on thermal bands, which depend on temperature differentiation between warm seawater and cool wastewater, freshwater, etc.

For the coastal stretch between Beirut and Tripoli, 34 major pollution sources were identified as a result of satellite image interpretation and field verification. These pollution sources produce a variety of marine pollution types (Table 2). From the satellite image interpretation and field surveys, sources and flow regimes of these pollution sources were assessed. Some of these types were previously mentioned by several authors (NCRS, 1999; Faour and Shaban, 2002; Khalaf, 2004; Nassif, 2004; Nakhleh, 2004; and CNRS, 2007). This shows that these sources still persist in the marine environment.

The pollution sources were distributed as: 6, 20 and 8 for detrital materials, wastewater and oil and chemical products respectively (Table 2). Most were found to include pollutants derived from

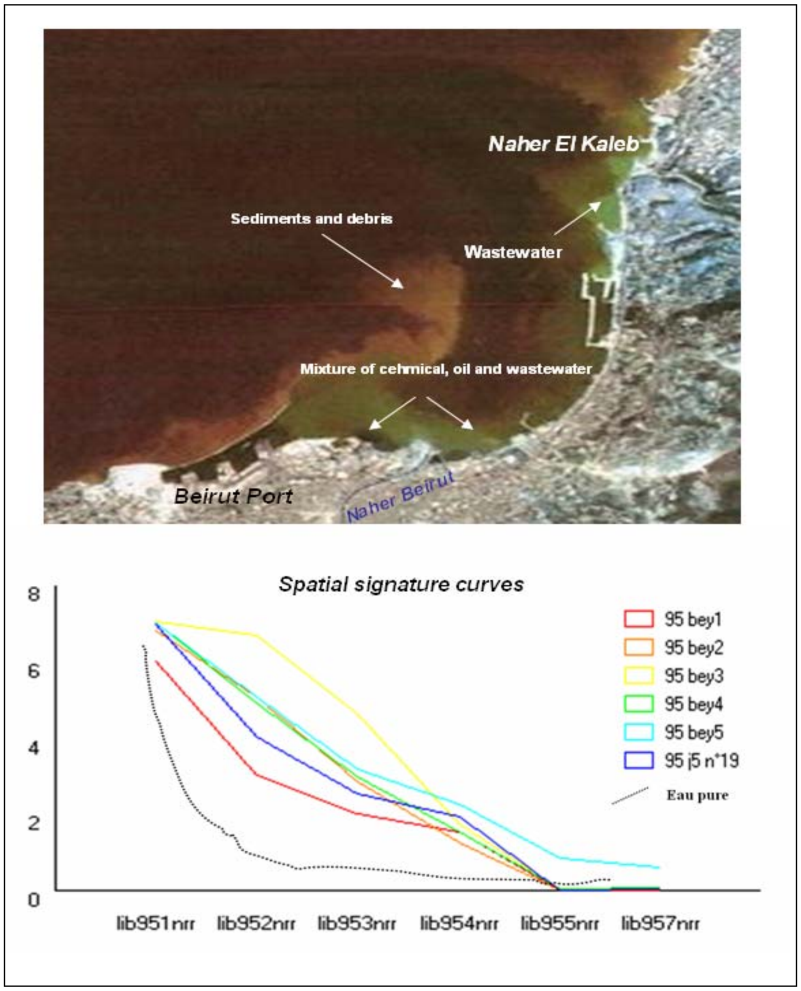

Figure 3. Application of different spatial signatures to identify transported materials to the sea near St. George Bay (adapted from Landsat 7 ETM+, 2001).

the terrestrial environment, while a small number was result from the oil slicks released from ships, especially near Beirut, Jounieh and Tripoli ports. In many instances, two or three pollution types were found mixed together. This mixing is either along the same transport path or after release into the sea.

Table 2. Major features of pollution sources along the coast.

Pollution type	Number & percentage*	Major aspects of release**	Average area	Sources
Detritial materials	6, 18%	Almost linear plumes perpendicular to the coast	Several kilometers long and a little bit narrower width, notably from the permanent watercourses	Streams and rivers and often mixed with polluted water and debris
Wastewater	20, 59%	Parallel and at angle to the coast	Mostly with several square hundreds of meters, with some exceptions to the major outfalls (e.g. Tabarja)	Sewers, outfalls, wastewater seeps and direct dumping for coastal settlements
Oil and chemical products	8, 23%	Chaotic and configured shapes	Several square hundreds of meters, along the coast and into the sea	Ports, ships, refineries, oil tanks and coastal industrial sites

* Number and percentage of pollution sites in the studied coastal stretch
** Aspects of release in wet season

Dynamics of pollutants transport

The dynamics of pollutant transport from terrestrial areas to the sea is well identified for the recognized sources of pollution obtained from the analysis of the sequential satellite images. The changes between wet and dry seasons were identified. It was obvious that there is a large variation in both dimensions and quality of the transported pollutants to the sea.

The detrital materials show the greatest change with time. Huge amounts of detritus are being loaded into the sea in wet seasons and after torrential rainfall, and large variations can be seen (Table 3). A predominant aspect of seasonal differences is the change from a linear release perpendicular to the coast in the wet season to curved during the dry season, carrying detrital materials along the shoreline. The residence time of detritus in sea water was found to be relatively short on the order of just few days (Table 3).

For wastewater, notably those pollutants derived from sewers, the mechanism is totally different. It involves a smaller-scale dimension compared with the detrital material dynamics

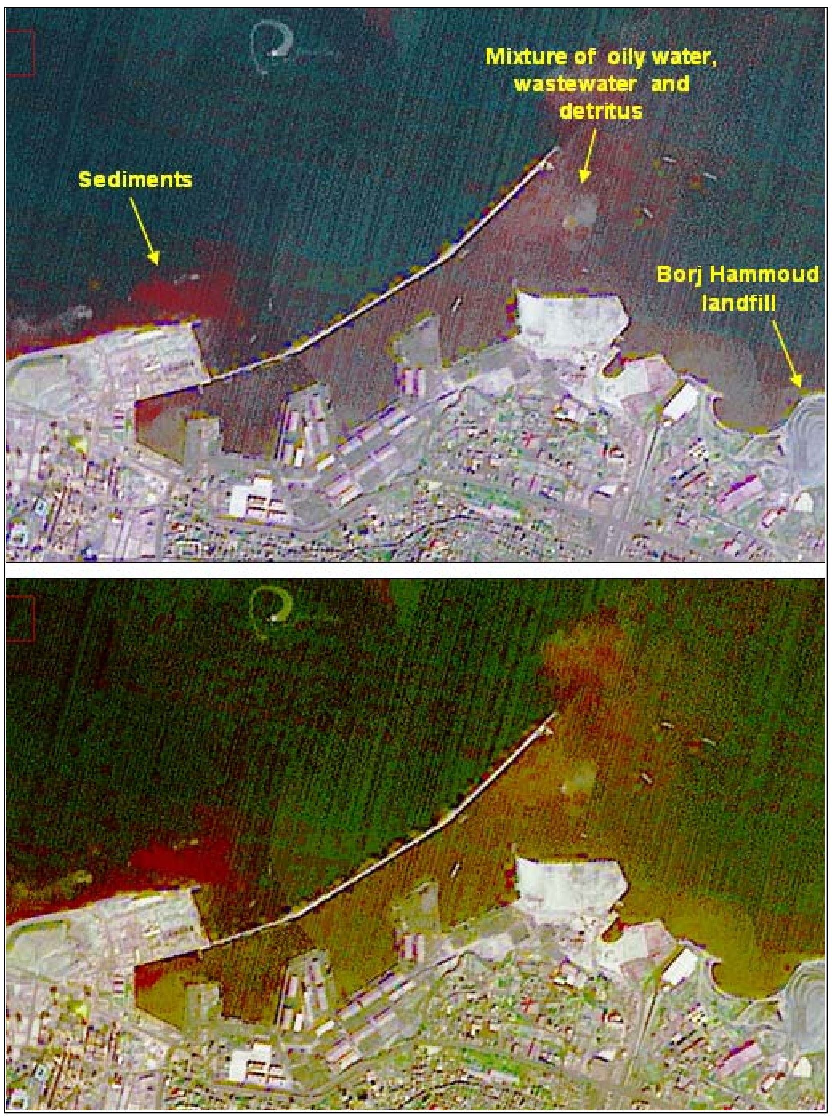

Figure 4. Example showing the application of different image processing procedures to identify anomalous signatures in the sea.

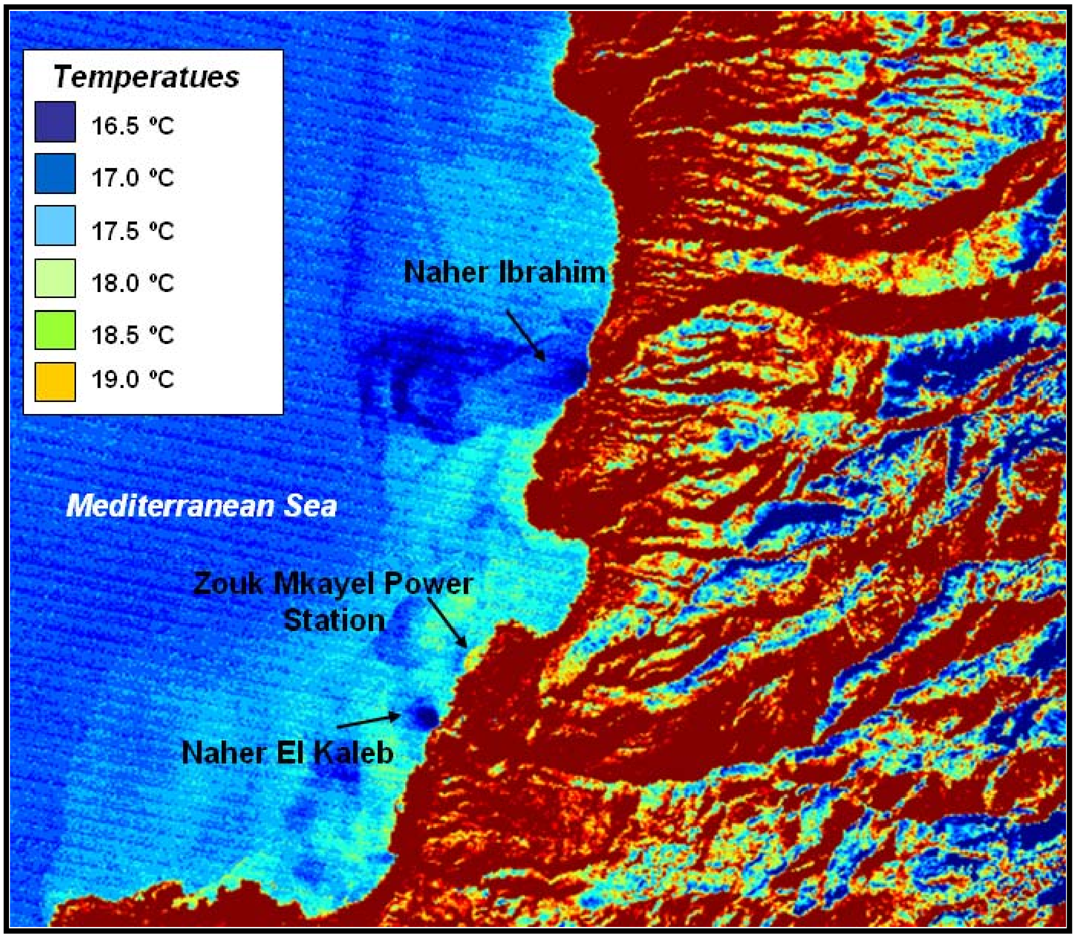

Figure 5. Example showing the application of thermal bands to identify anomalous signatures in the sea.

(Table 3). The residence time is much longer in the sea and may extend as long as a year. Variability in time is less than for detrital materials. Often wastewaters mix with detritus and become difficult to distinguish.

The same dynamics of wastewater probably applies for the oil and chemical products, but there is no consistency in all identified sites in many instances. In addition, the sources of oil and chemical products may be in the sea and sometimes reflect sudden events, notably those of oil spills. The configuration of these materials in the sea shows chaotic shapes depending on the material specifications, most notably viscosity (Table 3).

CONCLUSION

The marine environment of Lebanon has serious environmental problems. It threatens the marine ecosystem and creates harmful impacts to human health. The analysis of satellite images can show polluted areas, and the sources of pollution from land to the sea. Analysis of these images in a sequential time series can provide the behavior of pollutants with time.

The characteristics of terrain along the coast have an integral role in the process of pollutant release, along with human activities in the coastal zone. Steep slopes enhance the energy of flow for detritus and soluble materials, notably along watercourses. In addition, there are soft sediments that increase the tendency of these materials to be eroded.

Table 3. Major dynamics of pollutant transport along the coast.

Pollution type	Estimated variation in dimensions (Average in km^2)			Variation in aspects of release	
	Dry season	Wet season	Variation	Dry season	Wet season
Detritial materials	1-2	7-9	5	Curved to linear plumes, with stretching parallel to the sea	Almost linear plumes perpendicular to the coast
Wastewater	0.025-0.03	0.7-0.8	27	Diffusion with intermittent outlet, except the known major outfalls	Parallel and at angle to the coast
Oil and chemical products	0.015-0.02	0.5-0.55	30	Floating patches and slicks and some diffusion shapes	Chaotic and configured shapes

Land cover/use is also considered an influencing factor that exaggerates pollution along the coastline. The location of large Lebanese cities along the coast results in many negative impacts to the coastal environment.

Remotely sensed data has proven its capability to study these issues. It helped locate the sensitive areas of marine pollution, which were confirmed by field survey. The location of pollution hotspots along the coast in combination with their sources and mechanisms of transport on land allowed an assessment of the dynamic behavior of these sources. This concluded with a detailed evaluation of the three major types of pollution along the coast.

A more detailed and comprehensive study of the entire coastline of Lebanon is recommended. It should be accomplished as a yearly assessment to monitor all sensitive sources of marine pollution. This will provide valuable information to decision makers to fully implement an effective and comprehensive program of marine ecosystem protection and conservation in Lebanon.

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