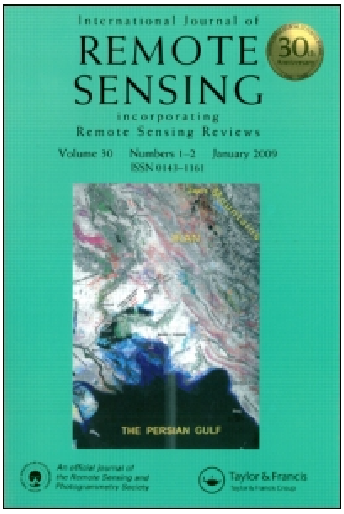

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Spectral enhancement of SPOT imagery data to assess marine pollution near Port Said, Egypt

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Satellite image data were used to detect, monitor and map different pollutants at five study sites along the El-Gamil beach, including El-Debba, El-Manasra, El-Fardous and El-Gamil inlets and the El-Gamil airport. The images were rectified and analysed by ERDAS IMAGINE 8.7. Image processing techniques were applied using ENVI 4.2 to analyse the SPOT image data (10 m resolution) for 2006. Image enhancement, principal component analysis (PCA), band ratios and supervised/unsupervised classifications were applied. Surface water samples were collected during the winter of 2005 and the summer of 2006. Water contamination was found to be higher in the summer than in the winter. SPOT image data from the summer, therefore, was selected to verify the results of metal analysis. Different pollutants detected along the El Manasra and El Debba sites are associated with industrial development, and discharge from natural gas companies and electric power generating stations. Significant water pollution is not unique to this region of the Mediterranean Sea, but is increasingly common at coastal locations throughout the globe. To protect both the marine environment and commercial interests that depend on clean water and beaches (e.g. beach resorts), effective wastewater management practices must be designed, implemented and maintained, along with reasonable development policies. Remote sensing may be an important tool for monitoring the effectiveness of any pollution mitigation strategies.

1. Introduction

Despite major strides in wastewater treatment and control of point and nonpoint source pollution, contamination of surface water remains a major global environmental concern. Developing effective methodology to monitor the quality of surface water has been, and continues to be, a major focus of research (Harrington *et al*. 1992, Gallie and Murtha 1993). An increasingly important tool for environmental monitoring is remote sensing and related areas of satellite-derived imaging. The information about the sea can be detected by electromagnetic radiation, and there are four primary quantities that can be observed from space, including the colour, the temperature, the roughness and the height of the sea (Robinson 2004). Many ocean features have surface signatures that can be studied by remote sensing from space or aircraft. Ocean colour is a good indicator of seawater properties and is detectable by remote sensing.

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Colour as perceived by the eye depends on the relative magnitude of radiation in three overlapping wavebands within the visible part of the spectrum.

Remote sensing technologies have been under development for nearly two decades to provide important data for multiple coastal water parameters, e.g. chlorophyll-*a*, turbidity, dissolved organic matter (DOM), total nitrogen, temperature and salinity (Yang 2005). The remote sensing techniques are based on either a radiative transfer algorithm or a statistical correlation model. Reflected light in the visible domain (wavelengths of 400–700 nm) is particularly useful in the study of upper ocean processes. Biological components of seawater absorb and scatter light effectively in this spectral range, which is called ocean colour related to the characteristics of the electromagnetic spectrum of water-leaving visible light (Miller *et al.* 2005). The most useful water quality data are collected by airborne remote sensing from small, shallow water bodies under cloudless conditions that allow for a high level of spatial resolution. Reliable information has been obtained with multiple satellite remote sensing systems, e.g. the Multi-Spectral Scanner (MSS), Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), SPOT HRV, IKONOS and Quickbird (Hellweger *et al.* 2004). These data were recorded as a quantitative measure of electromagnetic radiation that has either been reflected or emitted from terrestrial objects (Lindgren 1985).

Yang (2005) used ETM+ data to estimate chlorophyll-*a* concentrations in Pensacola Bay on the Gulf of Mexico. The *in situ* chlorophyll concentrations were estimated using band ratios as independent variables. Band 1/Band 3 was found to be the most effective in estimating chlorophyll-*a*. Using this ratio, Yang (2005) identified high concentrations of chlorophyll-*a* along the Gulf of Mexico coastline. The elevated levels were linked to an abundance of benthic algae, and also may have been due to phytoplankton since the chlorophyll-*a* measurements were higher near the outlets of several rivers (Yang 2005).

Change detection is the process of addressing the variation in the state of an object or phenomenon by observing it at different intervals in time. Monitoring these temporal fluctuations is one of the most important applications of remote sensing because of the availability of continuous, or frequent discrete, observations using a uniform data collection method (Anderson 1977, Ingram *et al.* 1981, Nelson 1983, Singh 1984, 1989).

The properties of the electromagnetic radiation received at a satellite depend on the interaction with the air/water interface (Martin 2004). The ocean is only viewed in three electromagnetic wavelength bands or windows: visible, infrared and microwave. In the visible and extending into the near-infrared, observations depend on reflected sunlight and are restricted to daytime cloud-free periods. The visible spectrum contains the only wavelengths at which light penetrates to oceanic depths greater than 10 m. Martin (2004) stated that two kinds of reflection are recorded in the visible spectrum. The first is the surface reflection at the interface of the solar radiance and skylight. The second is the diffuse reflection that is produced due to the propagation of the incident solar radiance across the interface into the water column; some of this radiation is reflected back as scattered radiance crossing the interface and return to the atmosphere. This is called water-leaving radiance, and is essential in measuring and monitoring water column properties such as chlorophyll concentration. In the infrared, the ocean is so highly absorbing that absorption and emission are confined to the top few microns of the sea surface. Although these observations are independent of daylight, they are still restricted to cloud-free time.

For the current study, SPOT images were used to monitor and analyse coastal water pollution at the El-Gamil area (figure 1). The image employed in this study was acquired in August 2006, with a resolution of 10 m (table 1). SPOT data were geometrically corrected based on the corrected images of Kaiser (2004) and further rectified to ground control points measured during the field study. Image data, combined with field inspection and chemical analyses, have been successfully applied along the western coast of the Port Said governorate to detect and monitor surface water pollution. Image processing are used to enhance the display of the image data and to highlight patterns which may not be clear at the image in its present state. The colour in which they are displayed can be changed. A variety of other operations are also possible, such as applying filters (Robinson 2004). The goal of this study was to apply image processing techniques, including image classification, band ratio and principal component analyses, to identify highly contaminated areas along the coastal zone of the study site.

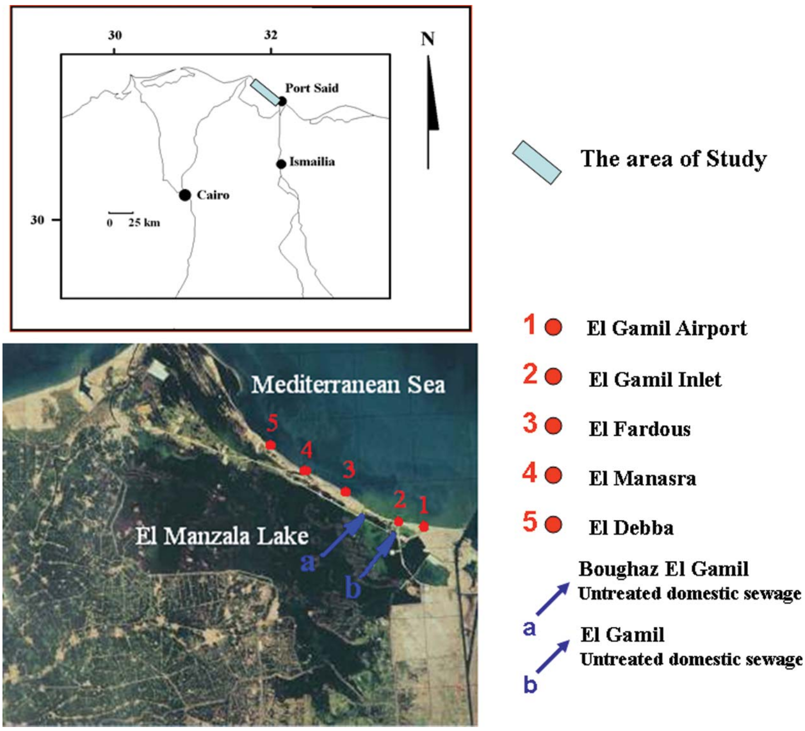

Figure 1. Location map of the study area.

Table 1. SPOT image data description.

Band	Description	Wavelength (μm)	Resolution (m)
b1	Blue	0.45–0.52	10
b2	Green	0.52–0.60	10
b3	Red	0.63–0.69	10
b4	Near-infrared	0.76–0.90	10

2. Surface water analyses

A total of 30 surface water samples were collected at a depth of 0.5 m from five selected sites along the El-Gamil coast during December 2005 and August 2006. Water samples were collected in one litre white polyethylene bottles, which were placed in an ice-box following collection, and transferred to the laboratory for storage at 4°C until analysis. Total concentrations of Fe, Mn, Zn, Cu, Pb and Cd metals were analysed using an atomic absorption spectrophotometer (AAS) (Perkin Elmer, Waltham, MA, USA, model 1200 A), at the El-Fostat Center, Cairo, Egypt, according to Standard Method 3110 (APHA 1992).

The concentrations of heavy metals were higher in the summer than in the winter (table 2). Even though there was variability among sites, the overall concentration range for a particular metal was relatively narrow, with no values that appeared to be unusual. Not surprisingly, Fe concentrations were the highest, ranging from 822.6 $\mu g\ g^{-1}$ at El Fardous to 896 $\mu g\ g^{-1}$ at El Debba. Cd concentrations were the lowest and ranged from 0.8 $\mu g\ g^{-1}$ at El Gamil inlet to 2.7 $\mu g\ g^{-1}$ at El Fardous inlet. A direct relationship was noticed between the concentration of heavy metals and the concentration of organic matter recorded in water samples. Organic matters range from 3.5% at El Debba to 4.8% at El Gamil inlet.

3. Image processing

Physical parameters related to the Earth's surface and atmosphere behave differently when observed at different space–time scales. Monitoring techniques, either remote or ground-based, rely on the principle that alterations in land cover will result in concurrent changes in the spectral signature of the affected land surface. The accuracy of the result is strongly dependent on the processing procedure, consisting mainly of geometric correction, image classification and spectral enhancement.

3.1 *Geometrical correction*

Raw digital images usually contain geometric distortions due to variations in altitude, attitude, Earth curvature and atmospheric refraction. Random distortions and residual, unknown systematic distortions are corrected by analysing well-distributed ground control points (GCPs) present within an image and for which accurate ground coordinates are available.

In this study, image rectification and registration were completed using ERDAS IMAGINE 8.7 (Leica Geosystems, Atlanta, USA) for the SPOT image in August 2006 (Path 178, Row 38) to monitor surface water pollution. The image was used to distinguish between water pollutants based on collected water samples during the summer of 2006. A second-order polynomial was used, as it provides an adequate transformation for registering a scene to geographical coordinates (lat/long), in the absence of significant relief (Bryant *et al.* 1985, Hardy 1985, Welch *et al.* 1985).

In order to improve the image registration and decrease the RMS errors, 25 well-distributed geographic GCPs were selected from 1:50 000 scale topographic maps and measured in the field using a Garmin 38 GPS (Global Positioning System) to be used for the geometric transformation model. These points represent features that are clearly seen in both the satellite image (source points) and topographic map (reference points). Since both the source and the corresponding reference points represent the same features, but with different X, Y coordinates, corrections were needed. The

Table 2. Results of heavy metals analysis of water samples collected from El-Gamil Coast during December 2005 and August 2006.

		Sites											
		El-Gamil Airport		El-Gamil Inlet		El-Fardous		El-Manasra		El-Debba		Overall	
Metal	Season	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Fe (μg g^{-1})	Winter	786	14.4	793.3	17.0	744	19.0	834.6	50.0	841.3	14.0	799.8	43.0
	Summer	872.6	27.0	832	24.9	822.6	14.7	846.6	30.2	896	15.0	853.9	34.1
Mn (μg g^{-1})	Winter	170	11.1	174.6	7.5	168.6	20.8	162.0	15.0	171.3	7.5	169.3	12.1
	Summer	198	5.2	190.6	9.0	180	7.2	169.3	13.0	187.3	6.4	185	12.4
Cd (μg g^{-1})	Winter	2.4	0.3	2.4	0.11	2.7	1.5	3.1	1.7	2.8	4.2	2.7	0.9
	Summer	2.6	0.2	0.8	1.3	2.7	0.11	2.6	0.2	2.4	0.2	2.6	0.9
Zn (μg g^{-1})	Winter	381.3	21.5	287.3	16.7	242.6	6.4	277.3	16.2	269.3	18.5	271.5	21.4
	Summer	300	17.4	271.3	17.2	283.3	16.2	294.6	32.5	282.6	20.0	286.3	20.9
Cu (μg g^{-1})	Winter	15.3	2.3	14.0	2.0	16.0	2.0	21.3	1.1	17.3	4.1	16.7	3.3
	Summer	13.3	3.0	12.6	2.3	14	2.0	19.3	1.1	18.6	1.1	15.5	3.3
Pb (μg g^{-1})	Winter	34.6	7.0	31.3	5.0	35.3	6.1	44	2.0	50.0	2.0	39.0	8.2
	Summer	42.6	8.0	40	6	41.3	6.4	50.6	4.1	56.0	7.2	46.1	8.4

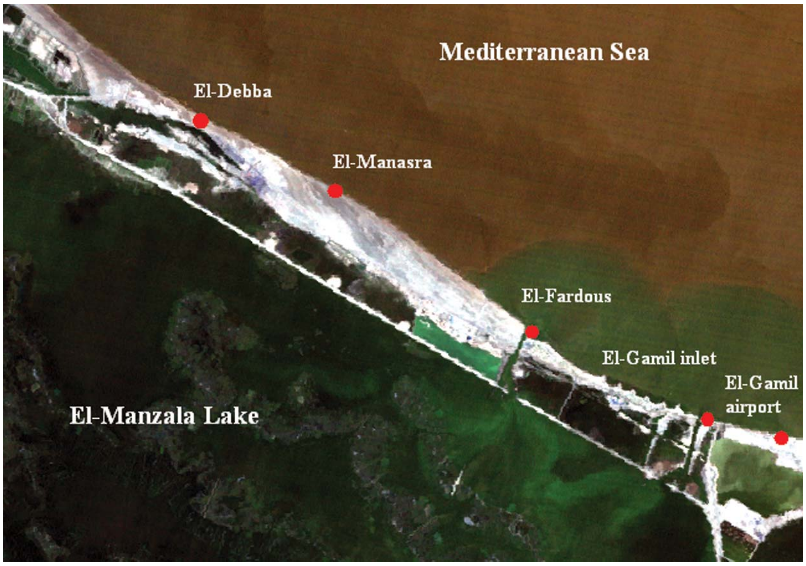

Figure 2. False colour composite of three SPOT bands (321 RGB) for 2006. Surface water pollution appears in green along the El Gamil coastal zone.

RMS errors were decreased from 0.4890 in X and 0.4567 in Y (Kaiser 2004) to 0.2314 in X and 0.2560 in Y in the present study. Although the cubic convolution is more complicated than both the nearest neighbour and the bilinear methods, it produces an image without the blackness that can occur with the nearest neighbour method due to the repetition of some pixel values. In addition, the output images do not have the over-smoothing problem associated with the bilinear method, which occurs as a result of the averaging process (Mather 1999).

The images were geometrically corrected to the Universal Transverse Mercator (UTM) projection with a 10 m grid. In this approach, the transferred 'synthetic' pixel values were determined by evaluating a block of 16 pixels from the original image matrix surrounding each output pixel. The simplest approach is to produce colour composite images that combine the information from three independent images. It is usual to apply contrast stretches individually to each channel before forming the colour composite, which then appears to have heightened colours; the result is called a false-colour composite (Robinson 2004). The most appropriate band combination used to create a false colour composite image showing drainage, agricultural and industrial waste products along the El-Gamil coastal zone was 321; RGB (red, green, blue); see figure 2.

3.2 *Image classification*

The basic premise in multi-spectral computer classification is that terrestrial objects possess sufficiently different reflectance properties (digital values commonly known as spectral signatures) in different regions of the electromagnetic spectrum. Based on these spectral signatures, natural and cultural surface features can be discriminated and a new output image created having a specific number of classes or categories (Singh 1989). Image classification is used to automatically categorize all pixels in an

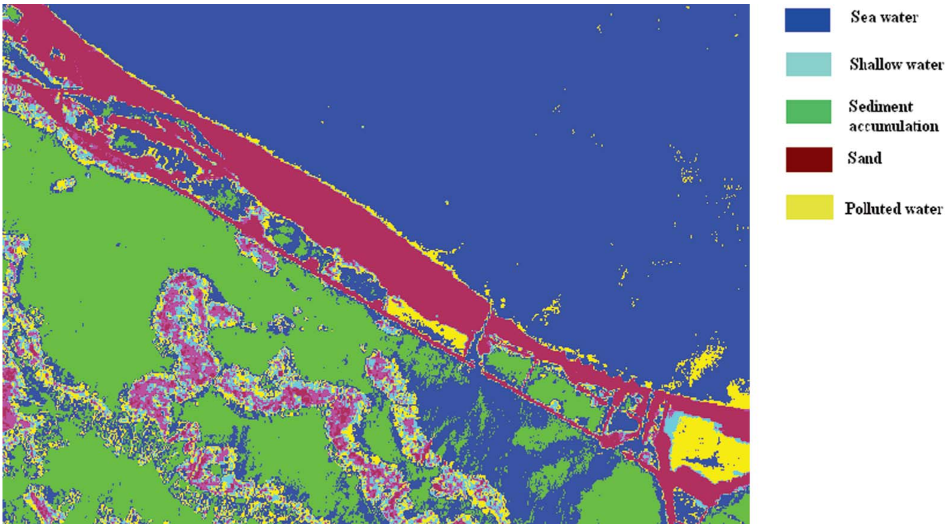

Figure 3. Supervised classification of the SPOT image for 2006, showing spectral classes at the El Gamil coastal zone.

image into land cover classes or themes. An essential aspect of any classification is the development of training samples for the spectral signatures of all objects existing within the scene. The statistics of these training samples characterize the different classes and enable the software to assign each point in the data to one of these classes. Accordingly, the classification techniques can be divided into two general types: unsupervised and supervised. Unsupervised classification was conducted using a histogram peak cluster technique to identify dense areas or frequently occurring pixels (Lillesand and Kiefer 2000). In the unsupervised approach, spectrally separable classes are determined and defined relative to their informational utility to form a supervised classification scheme. In the supervised approach the useful information categories are defined and examined for their spectral separability. Based on a histogram of the clustering results, five well-defined spectral classes were segregated (figure 3), including seawater (dark blue), shallow water (light blue), turbidity and sediment accumulation (green), beach sand (dark red) and polluted water (yellow). When the dissolved organic material exists with particulates they display a yellow-substance-like spectrum which causes overestimation of dissolved organic material concentration (Robinson 2004).

Each class was verified in the field using a Garmin 38 GPS unit; more than 25 ground data sites were visited and checked.

3.3 *Spectral enhancement*

Optical characteristics of the electromagnetic radiation detected by sensors are affected by some materials such as suspended sediment, phytoplankton and organic detritus that change the appearance (brightness and colour) of the sea. The presence of suspended particulate material contributes to the ocean colour due to the dumping of sewage-sludge waste or dredging spoils (Robinson 2004). The principal objective of enhancement techniques is to process a given image so that the result provides more extractable information, is more suitable than the original for a specific application and is more effective for visual display and interpretation. To obtain the maximum benefit from spectral enhancement, modification of a subjective image feature emphasizes certain information and improves the detectability of the target of interest by amplifying what may be very slight differences (Lillesand *et al.* 2004). Multispectral band ratioing and principal components were used to enhance the identification of surface water pollution at the study area.

3.3.1 Spectral ratioing. Empirical algorithms provide direct relationships between ratios of remote sensing reflectance or water-leaving radiances and seawater constituents such as chlorophyll (Miller *et al.* 2005). Different absorptions of phytoplankton represented by the ratio between the blue (443–490 nm) and green (555 nm) can be used to estimate chlorophyll. Ratio images are calculated through the division of DN values in one spectral band by corresponding values in another band (Lillesand and Kiefer 2004). The ratios for each cover type are nearly identical, irrespective of illumination conditions. The spectral ratio depends upon the particular reflectance characteristics of the surface features and capitalizes on small variations that might otherwise be unquantifiable. These small variations can occur due to a number of factors, one of which is the type of pollution. Water parameters can be estimated from spectral band ratios. There is no method which can be used essentially to determine the concentrations of the material in water which control its colour. Different types of models are used to simulate the water-leaving radiance spectrum and present the concentrations of chlorophyll, dissolved organic material and particulates (Robinson 2004). In this study, the most appropriate band ratio that reflected field observations and the results of chemical analyses was b1/b2 (figure 4). Surface water parameters are completely related to remotely sensed ocean colour data. As the ratio of blue (450 nm) to green (520 nm) (b1/b2; see table 1) gets lower, so the chlorophyll estimate increases (Robinson 2004). At higher chlorophyll concentrations, much blue light is observed.

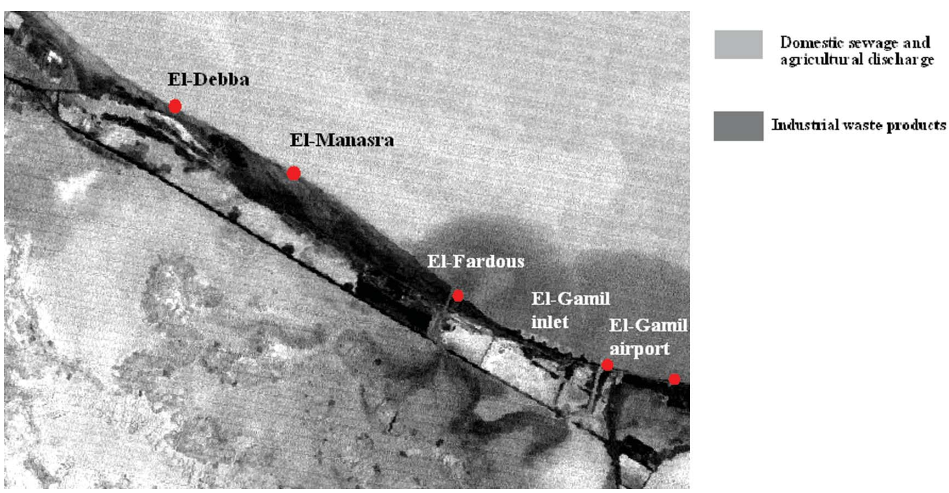

Figure 4. Results of using the b1/b2 band ratio of the SPOT image for 2006, showing different types of surface water pollution in the El Gamil coastal zone.

Therefore, domestic sewage and agricultural discharges, having high concentration of chlorophyll through the El Fardous and El Gamil inlets, appeared as a dark grey colour (low band ratios) while industrial waste products, having low concentration of chlorophyll at El Manasra, appeared as a light grey colour (high band ratios).

3.3.2 Principal component analysis. Principal component analysis (PCA) is used in a variety of applications, including remote sensing of alteration mapping, geologic mapping and water pollution (Loughlin 1991, Dwivedi and Sankar 1992). PCA was used to reduce redundancy in multispectral data to help in oceanographic interpretation (Robinson 2004). The original *n*-channel dataset was compressed into new, and fewer, components. A new set of variables were produced as a result of the calculation of a new coordinate system and condensing of the scene variance in the original data. This procedure enhances the spectral discrimination among different water pollutants. PCA results were verified by comparison to the water pollution distinctions identified through band ratioing. Statistical analyses showed that the first three components account for more than 97% of the total variance.

The oceanographic features influencing water colour are the phytoplankton, the concentration of pigments associated with primary production or dissolved organic material, the concentration of suspended particulates or the presence of a shallow seabed (Robinson 2004). These features appear in the second or the third component. The information constituting the surface layers of the sea can be interpreted from the light leaving the water surface. A three-band PC coloured composite was comprised of PC1 = red, PC2 = green and PC3 = blue. The three component images may be combined to form a colour composite image which can be treated as original data and used in the classification process and treated as an original data.

PC enhancement techniques are particularly appropriate when there is already a certain amount of information about the image (Lillesand and Kiefer 2000). Band

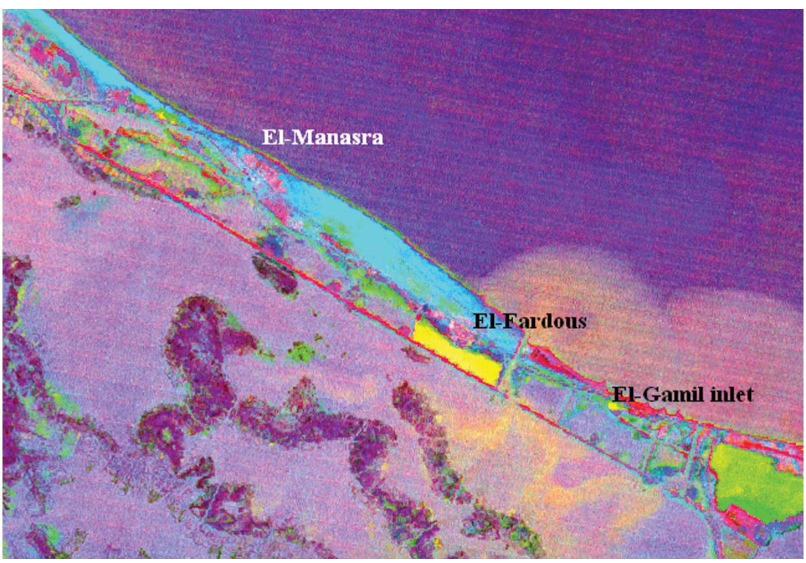

Figure 5. Band combination PC4 (red), PC3 (green) and PC2 (blue) of the SPOT image for 2006. Drainage discharge is shown as a pink colour in front of the El Fardous and El Gamil inlets.

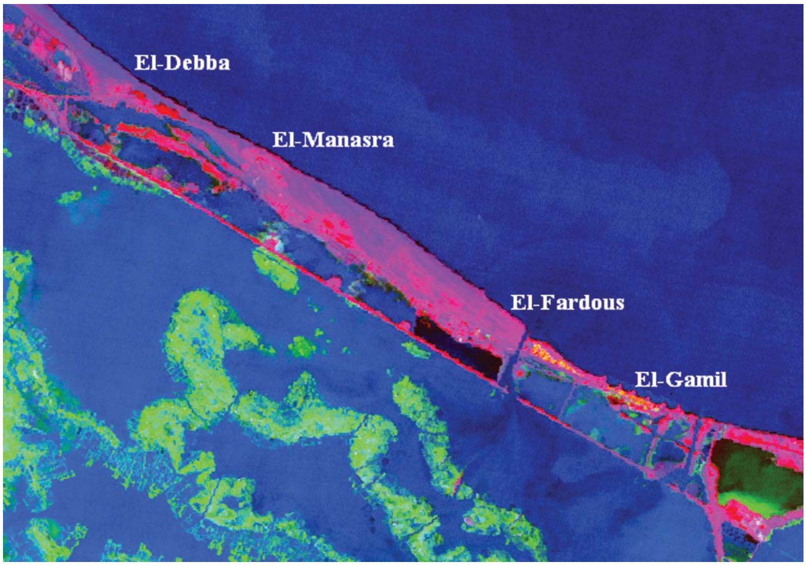

Figure 6. Band combination PC1 (red), PC2 (green) and PC3 (blue) of the SPOT image for 2006. Higher heavy metals and organic matter concentrations are shown as a black strip along the coastal zone.

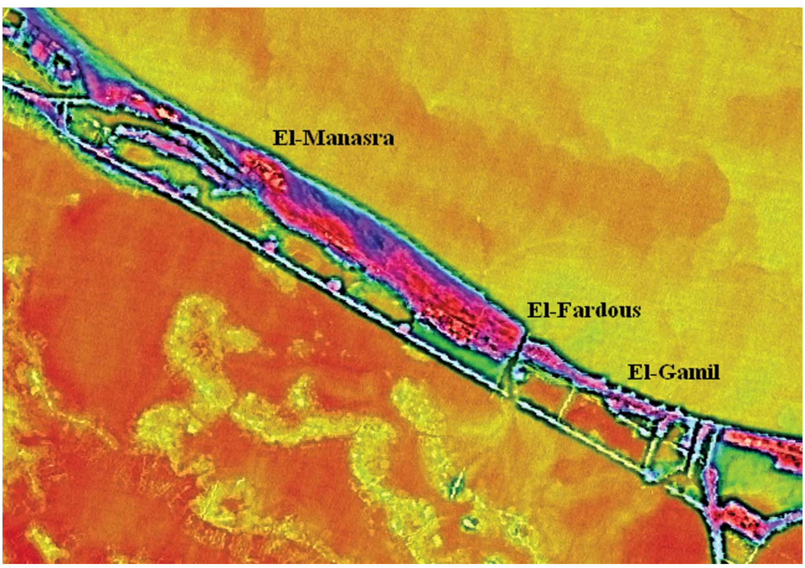

Figure 7. Synthetic colour image of the SPOT image for 2006, showing organic matter (dark strip) at El Manasra, El Fardous and El Gamil sites.

combination PC4 (red), PC3 (green) and PC2 (blue) was used to detect surface water pollution originating from drainage discharge through the El-Gamil and El-Fardous inlets (figure 5); the pollution appeared as a light pink colour. Red and dark pink colours were found along the coast at El Manasra and the El Fardous and El Gamil inlets. This signature was found to be associated with metals coming from domestic sewage and industrial and agricultural wastes. The band combination PC1, PC2 and PC3 (figure 6), combined with a synthetic colour image through the selection of band 3 as the input band (figure 7), were used to monitor surface water pollution. A dark black strip was identified along El-Debba, El-Manasra, El Fardous and El Gamil inlets, indicating water metal and organic matter contamination. Without the existence of particulates which scatter the light at the surface of water, no characteristic signature will appear and then dissolved organic material will show darkness (Robinson 2004). These pollutants likely originated from industrial and agricultural waste products, as well as the discharge of domestic wastewater along the coast.

4. Conclusion and discussion

Spectral enhancement of the data extracted from the 2006 SPOT image (10 m resolution) was used to detect and assess surface water pollution along the western coast of the Port Said governorate. Different types of pollutants, including agricultural, industrial, organic compounds and domestic discharge were identified by analysing surface water samples collected from the study area for heavy metals. Contaminants originating from agricultural and domestic sources were detected along the El Fardous and El Gamil inlets. Industrial pollutants were detected at the El Manasra and El Fardous sites. These contaminants were associated with natural gas companies, pipeline industries and an electric power generating station.

Image processing using ERDAS imagine 8.7 and ENVI 4.2 was utilized to verify the results obtained through chemical analysis and field observations. Supervised classification was used to identify five classes, including seawater (dark blue), shallow water (light blue), turbidity and sediment accumulation (green), beach sand (dark red) and polluted water (yellow). Band rationing b1/b2 was found to be the most appropriate spectral enhancement method used to detect sewage and agricultural discharges (dark grey colour) at the El Fardous and El Gamil inlets, and industrial waste products (light grey colour) at the El Manasra site. Surface water contamination was also identified by using the band combination of PC4 (red), PC3 (blue) and PC2 (blue), produced from PCA. A light pink colour was characteristic of drainage and sewage discharge at the El Fardous and El Gamil inlets. Elevated levels of heavy metals, from domestic sewage, industrial discharge from the natural gas companies and agricultural wastes at the El Manasra and El Gamil inlets, were distinguished by red and dark pink colours. A dark black strip was detected at the El Manasra, El Fardous and El Gamil inlets by using the band combination PC1, PC2 and PC3. This strip indicated a high concentration of organic matter from agricultural and domestic wastes, in combination with elevated heavy metals produced from industrial activities.

In conclusion, spectral enhancement of SPOT image data, coupled with field observations and chemical analyses, allowed for assessment and discrimination of different contaminants along the El Gamil coastal zone.

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