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Monitoring water quality in the coastal area of Tripoli (Lebanon) using high-resolution satellite data

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Abstract

Water quality in the coastal area of Tripoli (Lebanon) was assessed using Landsat 7 ETM+ data, to provide a first baseline for coastal resources management. The data were geometrically rectified to a standard geographical grid and brightness values were converted to reflectance through radiometric correction. Sea-truth data, collected in the field within 6 hours before/after the time of the satellite overpass, were used to derive empirical algorithms for chlorophyll-a concentration, Secchi disk depth and turbidity. Then, maps of the distribution of the selected water quality parameters were generated for the entire area of interest, and compared with analogous results obtained from SeaWiFS data. The maps indicate that the Tripoli coastal area is exposed to moderate eutrophic conditions, along most of its shoreline (in particular along the northern stretch), in correspondence with fluvial and wastewater runoff sources. The Landsat 7 ETM+ data proved useful for the intended application, and will be used to start a national database on water quality in the Lebanese coastal environment.

Keywords: Coast; Monitoring; Colour; High resolution; Multisensor

1. Introduction

Ocean colour radiometry has been successfully applied to the retrieval of phytoplankton biomass indices, such as chlorophyll-a concentration, and other water quality parameters, in various geographical locations and environmental settings. In general, this is done by virtue of empirical bio-optical algorithms — based, for example, on the inverse dependence of pigments concentration on the ratio between water-leaving radiance, or reflectance, measured in the blue and green parts on the light spectrum — for deriving a chlorophyll-a estimate (see *e.g.* Robinson, 2004). Measurements in the red and near-infrared may also be involved, in applications where the water quality parameter of interest is water transparency and/or turbidity (see *e.g.* Jensen, 2000).

A number of dedicated orbital sensors — such as the historical Coastal Zone Color Scanner (CZCS, 1978–1986) or the currently operational Sea-viewing

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Wide Field-of-view Sensor (SeaWiFS, since 1997), Moderate Resolution Imaging Spectroradiometer (MODIS), Terra and Aqua versions (since 1999 and 2002, respectively), and MEdium Resolution Imaging Spectrometer (MERIS, since 2002), to name just some of those most widely used — have been designed for monitoring the optical properties of marine waters. However, their spectral coverage and resolution (ranging primarily from 400 to 800 nm, with bandwidths of the order of 20 nm), as well as their spatial coverage and resolution (respectively of the order of 1000 to 2000 km swaths, and of 200 to 1200 m pixel size, or even more for derived data products), are mostly useful to cover broad expanses of open waters, where colour variations chiefly depend on the presence and abundance of planktonic pigments (in particular for the oligotrophic Mediterranean Sea, of interest in here; see, for example, D'Ortenzio et al. (2002)). Conversely, coastal and estuarine systems are often characterized by optically complex waters, with high concentrations of highly reflective water constituents, the colour of which is due also to dissolved organic matter and suspended sediments, and by much smaller geographical scales. Sensors originally designed for land observations, like Landsat's Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+), have proven to be more useful for assessing these systems, in spite of their radiometric limitations (bandwidths of 60 to 80 nm, in the visible, lower sensitivity in comparison to the instruments cited above), primarily because of their higher spatial resolution (30 m, or half that in panchromatic mode; see Baban (1997), Zhang et al. (2003) and Chang et al. (2004), for application examples).

The use of high-resolution optical remote sensing data is of particular value in those cases where no or little historical information exists for a certain coastal region. In the present study, an attempt has been made to describe the general conditions of coastal waters in the area of Tripoli (Lebanon), using synoptic satellite data. Since no other data of similar nature are available, at the present time, the aim is to provide a first baseline for coastal environmental assessment and management of this region. To this end, the mapping of water quality parameters in the study area was undertaken using Landsat 7 ETM+ data, calibrated by concurrent field data collected at sea. Also, a comparison of the results obtained with analogous SeaWiFS-derived data, with lower spatial resolution, highlighted the main advantages of the high-resolution approach taken here, and placed the current findings into a regional perspective.

The main reasons for the changes in the coastal and marine ecosystem observed in the study area are (a) discharges of municipal sewage and non-point loading from agriculture, which causes eutrophication, turbidity and oxygen deficiencies; (b) input of materials from the river indicated in the following as Nahr Abou-Ali, consisting mainly of dissolved nutrients and suspended solids; (c) contamination from the major open dump for solid waste and wastewater discharge of Tripoli, which is located in the same area. The main indicators of water quality chosen for this area, in line with the what reported in the literature cited above, are essentially chlorophyll-a, water transparency and turbidity. The first is an assimilation pigment of planktonic algae: its concentration in coastal waters can be considered, to a certain degree, a reliable indicator of phytoplankton biomass and production, as well as, more in general, of the level of eutrophication. Localized areas of high production are in some cases related to pollution from anthropogenic activities. Water transparency, often described in a simple – but effective – manner by Secchi Disk depth, or turbidity can also be used as an indicator of water quality, but is affected by many factors, such as the presence of phytoplankton and zooplankton, solid substances from coastal areas or rivers, and resuspended sediments.

In the following, the results of an *in situ* campaign conducted in the study area will be described, and compared with concurrent remotely sensed data, of the same area and of the eastern Mediterranean Sea at large. All of the parameters introduced above were measured at sea and then computed also from the satellite measurements, by virtue of statistical regression models. The inter-comparison of these data sets was used to derive a set of thematic maps for the coastal waters of Tripoli, showing the distribution of the selected water quality indicators. This case study provides an example of the current methodological innovations that are applicable to exploit the synergy of different kinds of data collection, in order to derive coastal water quality information in an area where none is available, using a combination of optical remote sensing techniques and a minimal amount of *in situ* measurements.

2. Materials and methods

2.1. Study area

The coastal area of Tripoli, located in the northern part of Lebanon, extends to the south and to the east from the headland of El Mina (Fig. 1). The continental

Table 1
Landsat 7 ETM+ bands, spectral interval and spatial resolution

ETM+ band	Name	Spectral interval (μm)	Spatial resolution (m)
Panchromatic band		0.52–0.90	15
Visible bands			
B1[a]	ETM+ 1 (blue)	0.45–0.51	
B2[a]	ETM+ 2 (green)	0.525–0.605	30
B3[a]	ETM+ 3 (red)	0.63–0.69	
NIR band	ETM+ 4	0.75–0.90	30
Mid-infrared bands	ETM+ 5	1.55–1.75	
	ETM+ 7	2.09–2.35	30
TIR band	ETM+ 6	10.40–12.50	60

[a] Identifier used in the following.

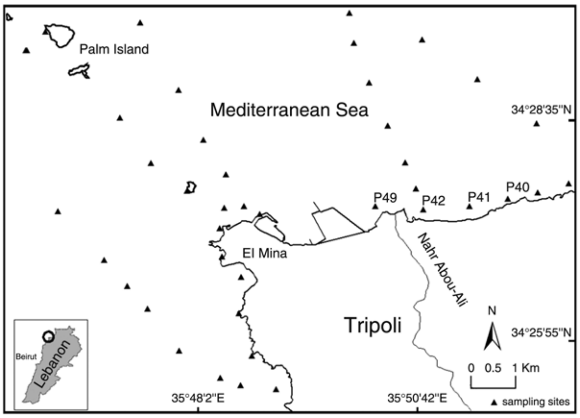

Fig. 1. Map of the Tripoli coastal area and sampling stations.

shelf in this area has a width of about 12 km. The average depth over the shelf is roughly 20 m, but the bathymetry is quite variable, especially off El Mina, where many shallow reefs and small islands occur (Goedicke, 1972). The Tripoli coastal area receives a sizeable freshwater input from the Nahr Abou-Ali (369 Mm^3/year). The major open dump for solid waste and wastewater discharge of Tripoli are located in the same area. The Council for Development and Reconstruction (CDR) of Lebanon is currently building a plant for primary treatment of sewage, to serve the city of Tripoli and surrounding areas, directly near the mouth of the Nahr Abou-Ali. However, at present, raw domestic and industrial wastewaters, from various sewer pipelines and drainage channels, are released at sea without treatment (200 Ml/day, in the year 2000). Due to the high nutrient input associated with this runoff, the Tripoli coastal/shelf zone plays an important role in supporting abundant marine life. The area of Palm Island (5 km offshore) is one of the few marine natural reserves in Lebanon.

2.2. Satellite data

Several studies have explored the possibility of exploiting high resolution satellite images, like TM data, for the determination of coastal water quality, with varying degrees of success (Bagheri and Dios, 1990; Tassan, 1993; Pattiaratchi et al., 1994). A Landsat 7 ETM+ image (path: 174, row: 36), dated 27 March 2003, was used for the present study. The image was acquired under clear sky and calm conditions. In addition to a panchromatic band, with 15 m spatial resolution, the Landsat 7 ETM+ includes 7 spectral bands, with 30 m spatial resolution for all except band 6, which is a thermal infrared band, with 60 m spatial resolution (Table 1).

A geometric correction was applied to the acquired Landsat ETM+ image, using ERDAS Imagine 9.0, a digital image processing and GIS software developed by Leica Geosystems, Atlanta, USA. First, the image was geometrically rectified to a Universal Transverse Mercator (UTM) projection (Zone 36; Datum: WGS84) using USGS 7.5 min quadrangle topographic maps. More than 35 Ground Control Points (GCPs) were selected from both the image and the topographic map. For the special interpolation portion of the geometric correction, a first-order, affine transformation was used. The RMS error was less than 0.5 pixel. The nearest neighbor resampling techniques was chosen as the last step in the rectification process, in order to assign the brightness values to the pixels in the output image (Jensen, 2005). According to the original data supplier (RADARSAT International, Canada), an atmospheric correction was applied, by performing a dark object subtraction, and an illumination correction by dividing all Digital Number (DN) values by the cosine of the sun elevation. In the present case, a radiometric correction of the Landsat ETM+ image was performed based on the Chavez (1996) COST method.

Table 2
Range of environmental variables measured in the Tripoli coastal area (N indicates the total Number of stations used, SD the Standard Deviation)

Variable	N	Mean	Maximum	Minimum	SD
Chlorophyll-a (mg m^{-3})	34	0.82	3.07	0.30	0.46
Secchi disk depth (m)	36	6.16	11.00	2.00	2.50
Turbidity (FTU)	45	2.34	8.43	0.58	1.86
Temperature (°C)	47	17.95	19.93	16.76	0.87

Table 3
Predictive algorithms derived from the matching *in situ* and Landsat 7 ETM+ data

(1a)	$\mathrm{Ln}(CHLA) = 1.67\text{–}3.94\ \mathrm{Ln}(B1) + 3.78\ \mathrm{Ln}(B2)$	$N = 34$	$R^2 = 0.723$
(1b)	$\mathrm{Ln}(CHLA) = 6.92274\text{–}5.75815[\mathrm{Ln}(B1)/\mathrm{Ln}(B3)]$	$N = 34$	$R^2 = 0.719$
(2)	$\mathrm{Ln}(SECCHI) = -7.27 + 4.84\ \mathrm{Ln}(B1) - 2.95\ \mathrm{Ln}(B2)$	$N = 35$	$R^2 = 0.54$
(3)	$\mathrm{Ln}(TURB) = 10.6823\text{–}5.6838\ \mathrm{Ln}(B1) + 3.5418\ \mathrm{Ln}(B2)$	$N = 45$	$R^2 = 0.57$

Because of possible residual errors in the remapping, and in order to take into account local uncertainties due to water dynamics, a window of 3 × 3 pixels around each pixel corresponding to a sampling station (see below) was considered for further processing. Then, the mean reflectance of the 3 × 3 window, instead of the central pixel, was extracted and used to derive empirical algorithms for water quality parameters, according to a technique widely used in similar works reported in the literature (see *e.g.* Baban (1997), Woodruff et al. (1999) and Braga et al. (2003)).

Additional satellite data, collected by SeaWiFS in March 2003, where also considered in the present study, for comparison with the available Landsat 7 ETM+ image. In this case, the processor used to compute chlorophyll-a concentration, using the OC4v4 algorithm, was the SeaWiFS Data Analysis System (SeaDAS), version 4.8 (see details in Gregg and Casey (2004), for bio-optical algorithms, and in Baith et al. (2001), for the software package, respectively). The atmospheric correction scheme adopted in this processor is based on the work by Gordon and Wang (1994) and subsequent developments (see *e.g.* Wang et al. (2005), and references therein). The comparison with the Landsat 7 ETM+ data involved SeaWiFS-derived chlorophyll-a maps for the same day, the day before and the day after the Landsat 7 overpass (*i.e.* 26, 27 and 28 March 2003), for the entire easternmost Mediterranean region, as well as the corresponding monthly mean map (*i.e.* March 2003), for the Lebanese coastal area.

2.3. In situ data collection

The acquisition of sea truth data, near-simultaneous with the Landsat 7 ETM+ image, was carried out in the coastal region under investigation. A group of 45 locations (shown in Fig. 1) was monitored within 6 hours before/after the time of the Landsat 7 overpass on 27 March 2003. The sampling stations were selected so as to represent the full range of environmental conditions expected in the study area. All stations were located by GPS (Trimble Geoexplorer), and all water quality parameters were determined *in situ* (the accuracy of the GPS measurements being 2 m and with differential <0.3 m). Weather conditions were optimal, with a cloudless sky. The spreading of river discharges was seen to be eastwards along the coastline, and driven by the dominant westerly and southwesterly winds.

Chlorophyll-a concentration was measured near the surface and below the surface, at 30–50 cm depth, using a Seapoint Chlorophyll Fluorometer (Oceano Instruments), with a measured sensitivity of 0.001 mg m^{-3} and a minimum detectable level 0.02 mg m^{-3} of chlorophyll-a. In order to avoid the interference of strong sunlight with the sensor, for the measurements at less than 1 m depth, the sensor was shaded from direct sunlight by a black disk put on the sea surface over the sensor. Secchi depth was measured with a 20 cm diameter black and white quadrate disk. Turbidity was measured near the surface and below the surface, at 50–60 cm depth, using a Seapoint Turbidity Meter (Oceano Instruments). Table 2 gives the range and some basic statistics of the environmental variables measured below the water surface over the whole Tripoli coastal area.

The mean chlorophyll-a concentration of the 34 sampling stations was 0.82 mg m^{-3}. A relatively high standard deviation (0.46 mg m^{-3}) was recorded, underlining the pronounced spatial variability of chlorophyll-a concentration. Higher concentrations were found along the coast. The highest concentration,

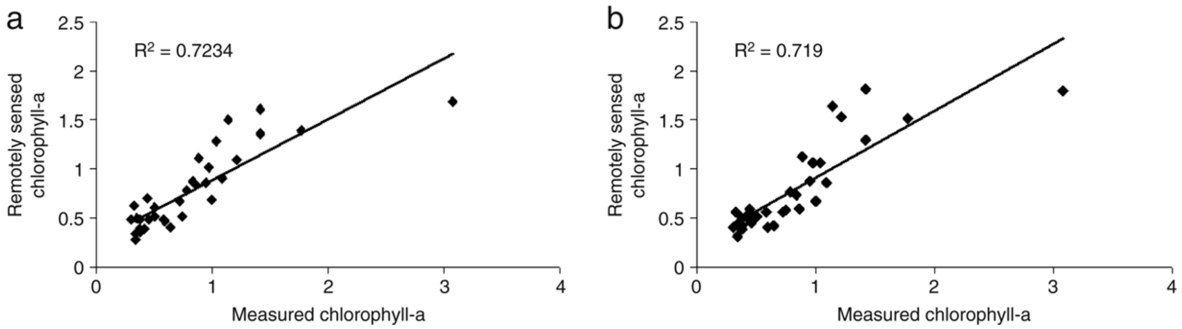

Fig. 2. Comparison between the surface chlorophyll-a concentrations derived from the predictive algorithms in Table 3, using (a) equation 1a and (b) equation 1b, and the *in situ* values.

3.07 mg m^{-3}, was recorded at station P40 (see Fig. 1), at the location of the El Baddawi sewage outfall. Relatively high concentrations, of 1.8 mg m^{-3}, 1.41 mg m^{-3} and 1.42 mg m^{-3}, were recorded at stations P41, P42, and P49, respectively (see Fig. 1), in the area where nutrients brought in by the Nahr Abou-Ali tend to have their maximum impact.

2.4. Statistical analysis and regression models

The rationale behind the development of *ad hoc* statistical algorithms, such as those developed for the present study area, is that – even when using data from high spatial resolution sensors like the Landsat 7 ETM+, characterized by wide spectral bandwidth and low sensitivity – the scattering and absorption characteristics of optical indicators can be assessed by means of a multispectral approach (Dekker et al., 1991). For example, previous studies have indicated that the optimal wavelength range for characterizing chlorophyll-a is between 0.4 µm and 0.9 µm. In this range, the prominent scattering/absorption features of chlorophyll-a are reflectance minima in the blue, between 0.4 and 0.5 µm, and in the red, at 0.68 µm, as well as reflectance maxima in the green, at 0.55 µm, and near-infrared, at 0.7 µm (Han, 1996). The basic principle of using band ratios, to estimate chlorophyll-a, is to select spectral bands that are representative of its absorption/ scattering features (Gin et al., 2002). Therefore, the four bands which are mostly associated with chlorophyll-a estimators are the blue, green, red, and near-infrared bands above (as in Han et al. (1994), Han and Rundquist (1997) and Gin et al. (2002)). The two bands which have the most penetration power, *i.e.* the blue one and the green one, can also be used to estimate Secchi disk depth and turbidity.

The analysis of the *in situ* data, collected on 27 March 2003 at the stations shown in Fig. 1, was carried out through statistical correlation and regression procedures. Logarithmically transformed chlorophyll-a, Secchi disk depth and turbidity were used as the dependent variables for the regression models, while the logarithmically transformed Landsat 7 ETM+ bands were used as the independent variables. The final selection of models was based on R^2, probability of a greater F-value for the overall model, and significance of the t-test for the regression parameters. A significant level of 0.05 was used for all models and regression parameters. The empirical algorithms reported in Table 3 (where B1, B2 and B3 correspond to the Landsat 7 ETM+ bands as indicated in Table 1) were found to be the best predictors of the natural log of the environmental parameters labeled CHLA (chlorophyll-a), SECCHI (Secchi disk depth) and TURB (turbidity). Water quality spatial maps were produced on the basis of the established regression models, using Modeler, a facility available in ERDAS Imagine. The related processing is based on a macro language defined as Spatial Modeler Language (SML).

Concerning the performance of the predictors, Fig. 2 shows a comparison between the surface chlorophyll-a concentrations derived from the algorithms, according to equations (1a) and (1b), and the corresponding *in situ* measurements. The values predicted from the algorithms show a reasonable amount of scatter against the observed values. In both cases, the results appear to be statistically significant. However, it is worth noting that the algorithm based on B1 (blue) and B2 (green) performed slightly better than that based on B1 (blue) and B3 (red). The results obtained for Secchi disk depth and turbidity, with algorithms based again on B1 and B2, appear to be less significant. Once the obvious limitations of a single-date approach to the generation of the empirical algorithms is taken into account, the CHLA, SECCHI and TURB spatial maps derived from the Landsat 7 ETM+ image provide an expanded, novel view of the water quality parameters distribution

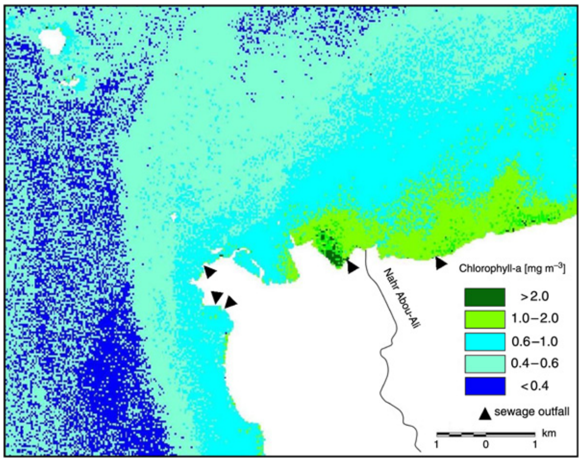

Fig. 3. Chlorophyll-a (algorithm 1a, Table 3) map of the Tripoli coastal area. From Landsat 7 ETM+ data, at 30 m resolution, 27 March 2003.

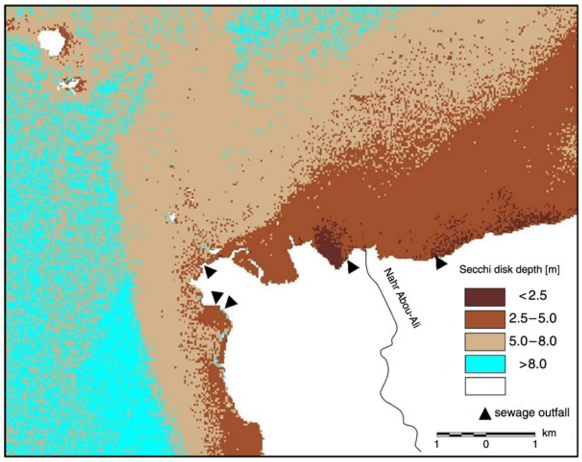

Fig. 4. Secchi disk depth (algorithm 2, Table 3) map of the Tripoli coastal area. From Landsat 7 ETM+ data, at 30 m resolution, 27 March 2003.

that can be obtained using the simple, yet effective, methodology above.

3. Results and discussion

The chlorophyll-a map of the area under investigation, generated using algorithm (1a), is shown in Fig. 3, while the water transparency (Secchi disk depth) map generated using algorithm (2) and the turbidity map generated using algorithm (3) are shown in Figs. 4 and 5, respectively. These color-coded maps represent a first synoptic view of water quality parameters for the Tripoli coastal area viable to date, albeit they only describe the state of surface waters on 27 March 2003. Plumes of turbid waters, where transparency is low and chlorophyll-a relatively high, can be observed at several hotspots adjacent to the shoreline, in particular along the northern coastal stretch. Sewage outfalls, at various locations (indicated in Figs. 3–5), as well as the Nahr Abou-Ali, may be at least partly responsible for such conditions, due to their abundant release of pigmented materials (and nutrients). The main gradients are sloping in the offshore direction, where the surface patterns seem to be oriented toward the north-east, possibly in line with the prevailing current (Alhammoud et al., 2005; Kabbara et al., 2006).

The chlorophyll-a levels are above 0.6 mg m^{-3} for most of the coastal area considered. These values compare well with typical values (ranging between 0.5 and 1.0 mg m^{-3}), reported for other Mediterranean near-coastal regions exposed to moderate eutrophication (UNEP-WHO, 1988). The hotspots along the northern coastal stretch, where water Secchi depths fall below the critical values of 2 to 3 m (UNEP-WHO, 1982), display concentrations up to and above 2.0 mg m^{-3}.

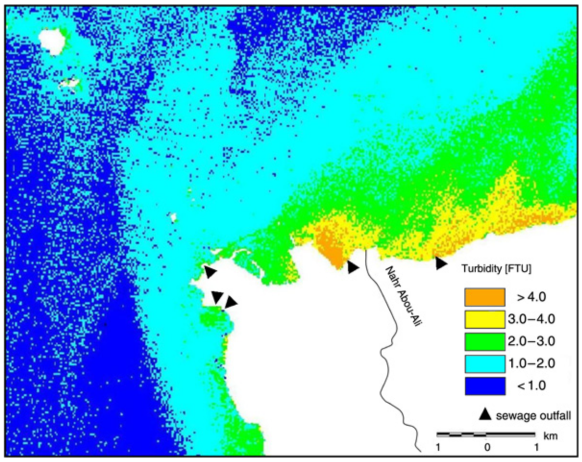

Fig. 5. Turbidity map (algorithm 3, Table 3) of the Tripoli coastal area. From Landsat 7 ETM+ data, at 30 m resolution, 27 March 2003.

The comparison of the chlorophyll-a map with the concurrent (±1 day) SeaWiFS-derived imagery, covering the entire eastern Mediterranean region (Fig. 6), shows that in both cases offshore waters present concentrations up to approximately 0.4 mg m^{-3} (except for a number of large-scale coastal plumes, where the concentration can be twice that value). Inshore waters, in the images of Fig. 6, present concentrations around or above 1.0 mg m^{-3}, but the innermost coastal pixels appear to be systematically masked out. This, of course, because the algorithms used to estimate chlorophyll-a, for a sensor with narrow spectral bandwidth and high sensitivity such as SeaWiFS, become generally unreliable in optically complex waters, where the

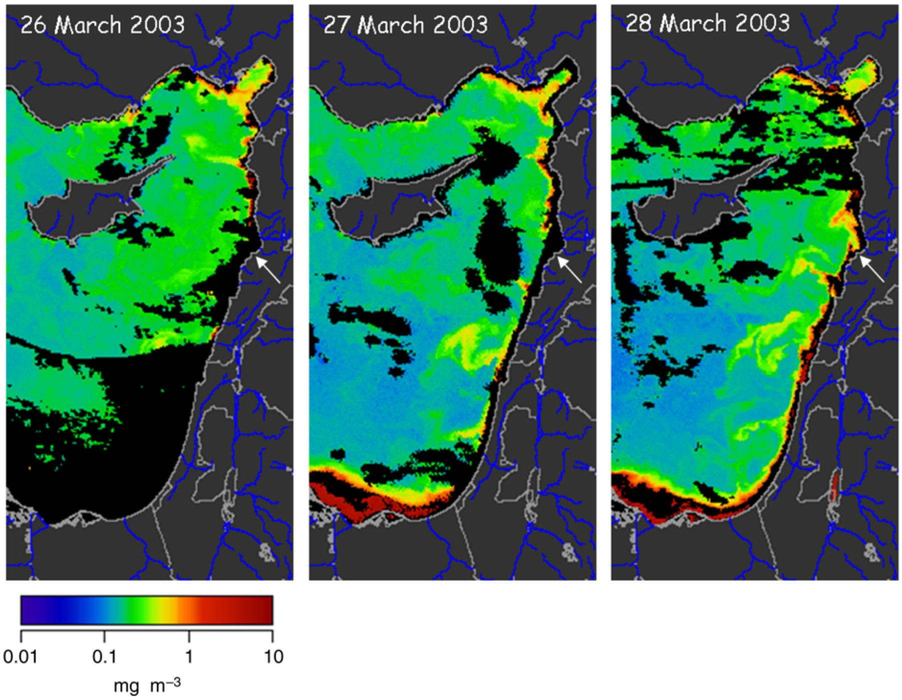

Fig. 6. Chlorophyll-a maps of the eastern Mediterranean Sea. Black pixels represent clouds, points contaminated by signal noise or near-coastal areas where the processing algorithm failed to derive a significant chlorophyll-a value. The white arrows indicate the area of Tripoli. From SeaWiFS data, at 2 km resolution; 26, 27 and 28 March 2003.

concentration of other optically active material such as dissolved organic matter and suspended inorganic particles is significantly high (IOCCG, 2000). The problem cannot be solved even by constructing long term mean images, such as the monthly mean for March 2007 shown in Fig. 7. While clouds and other transient features disappear in such a composite, the innermost coastal stretch continues to be masked out, testifying the persisting high concentrations of water constituents in these waters. Indeed, it is precisely the strong reflectivity, due to these high concentrations, that renders the application of land-observing sensors like the Landsat 7 ETM+ possible for the assessment of water optical properties in coastal zones.

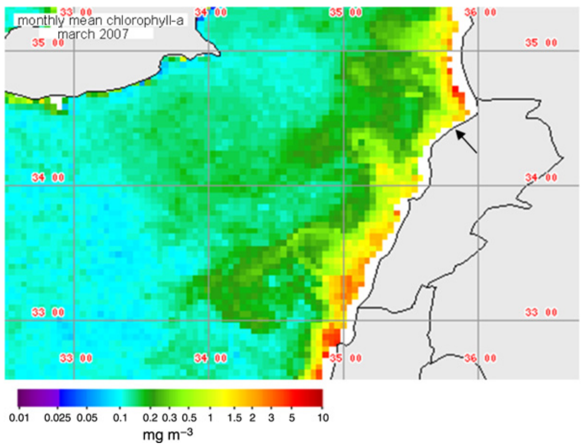

Fig. 7. Monthly mean chlorophyll-a map of Lebanese waters. White pixels along the coast represent areas where the processing algorithm failed systematically to derive significant chlorophyll-a values. The black arrow indicates the area of Tripoli. From SeaWiFS data, at 5 km resolution; March 2003.

4. Conclusions

Ocean colour radiometry of the coast around Tripoli indicates that this area is exposed to the risk of developing eutrophic conditions, along most of its shoreline (in particular along the northern stretch, due east of the headland of El Mina). This appears to be linked to the presence of fluvial and wastewater runoff sources. The combination of spectral and spatial resolution of the Landsat 7 ETM+ proved useful for the intended application, which generated a first set of thematic maps showing the distribution of selected water quality parameters. The maps can be compared with large scale assessments of analogous parameters, derived from SeaWiFS data, to place the local results obtained from the Landsat 7 ETM+ into a regional perspective. This information, still to be evaluated at seasonal and interannual scales in future studies, will be used to start a national database on water quality for the Lebanese coastal environment.

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