Application of remote sensing to site characterisation and environmental change analysis of North African coastal lagoons

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Abstract This article describes the use of satellite imagery for identifying key environmental characteristics within three North African coastal lagoons (Merja Zerga, Morocco; Ghar El Melh, Tunisia and Lake Manzala, Egypt) and for detecting the major environmental changes within these environments. A combination of Landsat MSS, Landsat TM, Landsat ETM+ and ASTER imagery was acquired for the three sites for a period covering the last three decades (1972–2004). Following geometric correction and enhancement, the interpretation of the most recent image acquired for each of the three lagoons provides important insights into their current conditions. For Merja Zerga, these include the distribution of the largest channels which drain extensive inter-tidal mudflats and the two major depositional features associated with sources of freshwater. The distribution of marginal aquatic vegetation is highlighted as is the intensive use of the surrounding landscape for agriculture. Intensive agriculture around Ghar El Melh is also indicated. The influence of the Mejerda River, which was diverted away from the lagoon over 100 years ago, is shown to persist as a residual area of deltaic deposits in shallow water that has been eroded over time. Coastal processes including the direction of the alongshore sediment transport and the influence of engineering work associated with port construction can also be recognised. Within Lake Manzala, vegetated islands divide the lake into a series of sub-basins which can be clearly distinguished. The large influence of human activities within this lake can be identified and include reclamation for agriculture and the conversion of parts of the lake bed for fish farms. The historical images available for the three lagoons provide important insights into decadal scale changes, which have been greatest at Lake Manzala. Since the early 1970s large parts of the lake, in particular in the southwest where the shoreline has migrated northwards, have been reclaimed. Major engineering

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works, such as the El Salam Canal and road embankments, are shown to have resulted in significant lake change. The distribution of emergent vegetation within the lake has also changed. Classification of images for this lake into open water, vegetation and land enables the quantification of these changes. Between 1973 and 2003, the lake declined in area by approximately 50%. Changes at Merja Zerga over the last three decades include reconfiguration of the marine outlet and the expansion of the internal delta at the end of the Nador Canal. The images of this site clearly demonstrate the intensification of agriculture around the lagoon. The most marked changes evident within the images of Ghar El Melh concern the sand bars that separate the lagoon from the sea. Geomorphological processes operating within the coastal zone have resulted in the straightening of the bars with central sections migrating out towards the sea. Remote sensing is established as a promising application for detecting the quantitative surface cover changes in coastal lagoons and their near landscapes.

Introduction

Remotely sensed images can be used as a tool to map ecosystems and to detect, monitor and evaluate changes within them thereby supporting the development of resource management strategies. Satellite and airborne systems offer major opportunities for monitoring large scale, earth surface characteristics and provide a database for change detection studies. Remotely sensed data can be used to span temporal and spatial scales ranging from local to aggregated global systems (Graetz, 1990). Monitoring global, regional and local areas can be performed by restricting the analysis to a single sensor series or by using different satellite data. With the availability of data from remote sensing satellites such as the Landsat series, it has become cost effective and convenient to acquire multi-date images over a greater array of spatial and temporal scales than was possible with aerial photography. The temporal resolution of data (the ability to obtain repeated

coverage of a specific geographic area, 16 days in the case of Landsat TM) from such sources permits regular image acquisition over the same area enabling change detection at relatively high temporal frequency (Lillesand et al., 2008).

Common types of detectable land cover change, which can be monitored using remotely sensed data, include vegetation disturbance and regeneration, agricultural intensification, urban expansion, spatial changes in aquatic ecosystems and hence surface water extent, as well as a variety of soil disturbance processes including overgrazing and soil erosion (e.g. Milne, 1988; Hall et al., 1991). The application of remote sensing for biodiversity and conservation over a range of spatial scales is reviewed by Turner et al. (2003), who emphasised the great potential of the approach. Remote sensing techniques can enable ecologists and resource managers to monitor the vegetation condition and detect environmental change trends in regions where difficult terrain, poor access, and extreme climate conditions make regular field investigations difficult. Satellite data are also suitable for inventorying the type, quality, distribution, productivity and biomass condition of natural as well as planted vegetation at a range of spatial scales (Hobbs, 1990; Milne & O'Neill, 1990; Franklin, 1991; Hall et al., 1991;, Turner et al., 2003). Land cover change detection and overall land use classification (e.g. Ambrose & Shag, 1990; Teng, 1990; Petit & Lambin, 2001) have global applications especially regarding assessments of the magnitude and rate of conversion of natural landscapes into high productivity agricultural or urbanised systems. Satellite and/or airborne data has been demonstrated to have particular use for monitoring water and vegetation changes within aquatic ecosystems including wetlands (e.g. Hardisky et al., 1986; Howman, 1988; Hess et al., 2003; Ozemi & Bauer, 2004, Cózar et al., 2005).

In Africa, remote sensing has made major contributions to monitoring a variety of wetland systems (e.g. Fuller et al., 1998; Munyati, 2000; De Roeck et al., 2008). Landsat data, for example, has enabled the identification of the impacts of both natural processes and human interventions on African lakes, freshwater ecosystems and wetlands (UNEP, 2005). Results from studies utilising data from these sources have revealed that pollution resulting from land-use changes, environmental modification and other practices associated with rapid population increase, and

water abstraction have caused or accelerated many negative changes in the continent's lakes (e.g. Randazzo et al., 1998, Scheren et al., 2000). The main threats to water quality in Africa are perceived to include eutrophication, pollution, increasing water demand and the proliferation of invasive aquatic plants such as the water hyacinth (e.g. Albright et al., 2004). One study of Lake Chad carried out within NASA's earth observing system programme showed that the lake shrank to one-twentieth of its original size during the last 35 years (NASA, 2001). In North Africa, remote sensing has been used to monitor the development of Lake Nasser including the new delta in its southern section and environmental changes in Lake Ichkeul, Tunisia, (NASA, 2005a, b). The use of remotely sensed data for monitoring North African wetlands has much potential (Flower, 1998) when combined with ground surveys and existing field data. Turner et al. (2003) stressed the importance of obtaining validatory ground evidence to help to interpret remote sensing products. For the management of North African coastal lagoons, remote sensing techniques provide an exceptional means of distinguishing spatial vegetation cover as well as determining the extent of open water, marginal disturbance and water quality (Ahmed & Donia, 2007; Ahmed & El-Leithy, 2008). This study aims to apply remote sensing techniques to three North African lagoons to both assess spatial status and to detect recent environmental change. It was undertaken as part of MELMARINA (Monitoring and Modelling Coastal Lagoons: Making Management Tools for Aquatic Resources in North Africa), a 3-year integrated hydro-ecological monitoring and modelling project funded through the EU INCO-Med programme (see Flower & Thompson, 2009).

The MELMARINA primary lagoons

Three primary lagoons, one in each of the three North African countries who participated in the MELMARINA project, were identified: Merja Zerga (Morocco), Ghar El Melh (Tunisia) and Lake Manzala (Egypt) (Fig. 1). These lagoons were the focus of field survey and monitoring activities (e.g. Ramdani et al., 2009, Thompson et al., 2009) as well as hydro-ecological modelling (e.g. Rasmussen et al., 2009a, b) and the remote sensing reported in this article. A series of secondary sites was also identified to provide context for the primary sites (see Flower & Thompson, 2009). They were not, however, subjected to remote sensing analysis.

Detailed descriptions of the three primary lagoons are provided by Ayache et al. (2009). They are strongly contrasted according to their physical and biological characteristics. All three are shallow water bodies (<2 m deep) linked to the sea through one or more well-defined connections. They vary in size from c.13 (Merja Zerga) to c.700 km^2 (Manzala) and differ in water quality. Merja Zerga is flushed daily by the relatively large Atlantic tides whereas Ghar El Melh and Lake Manzala, being confluent with the Mediterranean, are much less affected by tidal cycles (see Thompson et al., 2009). All three lagoons occur at the termini of inland drainage systems, which have all been subjected to significant human modification. Merja Zerga receives freshwater from two highly seasonal inflows, one of which (the Nador Canal) is artificial comprising drainage water. The volumes of these inflows are smaller in comparison to those associated with tidal flushing by sea water. Freshwater inflows to Ghar El Melh are also seasonal and usually very small except when exceptional floods
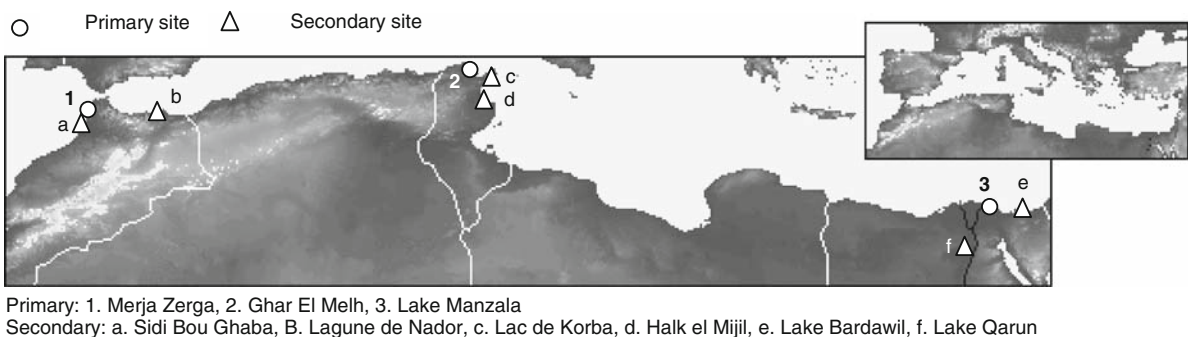

Primary: 1. Merja Zerga, 2. Ghar El Melh, 3. Lake Manzala
Secondary: a. Sidi Bou Ghaba, B. Lagune de Nador, c. Lac de Korba, d. Halk el Mijil, e. Lake Bardawil, f. Lake Qarun

Fig. 1 The MELMARINA lagoons

link the lagoon with the Mejerda River, which historically discharged into the lagoon. As a result of the relatively small and seasonal freshwater inflows, both Merja Zerga and Ghar El Melh are usually dominated by marine water, especially in summer. On the other hand, Lake Manzala has become predominantly freshwater since it now receives large volumes of agricultural and domestic drainage from drains along its southern borders (e.g. Ayache et al., 2009; Stanley, 1996; Stanley and Warne, 1993; Thompson et al., 2009). This last site is characterised by extensive within lake emergent vegetation, which is largely restricted to marginal areas within Merja Zerga and Ghar El Melh.

Methods

This study employed remotely sensed image processing supported by expert opinion on site characteristics obtained during the course of MELMARINA field programs within each of the three primary lagoons. The aims were twofold; first to demonstrate the utility of remotely sensed imagery for identifying key environmental features within coastal lagoons. This was undertaken for all three of the MELMARINA lagoons using imagery acquired during or immediately before the initiation of the field programs (June 2003–September 2004). The second aim was to employ historical remotely sensed data to reveal the long-term changes in the bio-physical characteristics of the lagoons. Although this was undertaken for all three MELMARINA primary lagoons, a particular focus was Lake Manzala for which image classification techniques were applied. This was due to the particular characteristics of the site and the large changes witnessed within the lake over the last three decades (e.g. Ayache et al., 2009). The following sections describe the different stages of the analysis.

Image identification and acquisition

The initial aim for the analysis of contemporary images was to employ data from the same sensor, the Enhanced Thematic Mapper Plus (ETM+) on the Landsat 7 platform, for each lagoon. Images for this sensor consist of eight spectral bands with spatial resolutions of 30 m for bands 1–5 (recording wavelengths between 0.45 and 1.75 μm) and 7 (2.09–

2.35 μm), 60 m for band 6 (thermal infrared, 10.40–12.50 μm) and 15 m for band 8 (panchromatic, 0.52–0.90 μm) (Graetz, 1990). A suitable, cloud free image of Lake Manzala was available from this source for 05/02/2003. However, an unsuccessful review of available data for the other two lagoons, combined with the failure of the Scan Line Corrector on the sensor in May 2003 which impacted data quality (e.g. Maxwell et al., 2007; Zhang et al., 2007) necessitated the use of alternative imagery. Therefore, data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument on the Terra satellite were employed. This instrument records data from 14 spectral bands from the visible to the thermal infrared wavelengths. The visible and near infrared (VNIR) bands (1–4) cover a similar wavelength range as bands 1–5 of Landsat ETM+ (0.52–0.86 μm) at 15 m resolution, higher than that provided by Landsat ETM+ (Abdeen et al., 2002; Marçal et al., 2005; Gao & Liu, 2008). ASTER images from 23/07/2004 and 01/09/2003 were acquired for Merja Zerga and Ghar El Melh, respectively.

A suite of historical images for the three lagoons were acquired to facilitate the identification of decadal scale change (Table 1). One Landsat ETM+ scene from 2001 was available for both Merja Zerga and Ghar El Melh. Landsat Thematic Mapper (TM) imagery was acquired for the mid-1980s to the early 1990s. The predecessor of Landsat ETM+, Landat TM's seven bands cover a similarly wide range of the electromagnetic spectrum from the visible range (0.45–0.69 μm), to near infrared (0.76–0.90 μm) and mid infrared (1.55–2.35 μm), up to the thermal infrared band (10.4 – 12.5 μm) (Jensen, 1986). With the exception of the thermal infrared band (120 m), the spatial resolution of the data is 30 m. Landsat Multi-Spectral Scanner (MSS) imagery were acquired for the 1970s and early 1980s. The four bands of this sensor cover the visible to near infrared part of the electromagnetic spectrum (0.5–1.1 μm) at the larger pixel size of 79 m (Jensen, 1986). As summarised in Table 1, in total four images covering the period 1979–2004 and 1972–2003 were available for Merja Zerga and Ghar El Melh, respectively. Six images (1973–2003) were employed for Lake Manzala. More images for this last site were employed since they were already available within the data archive of the National

Table 1 Summary of remotely sensed imagery available for the MELMARINA primary lagoons

Merja Zerga		Ghar EL Melh		Lake Manzala	
Date	Sensor	Date	Sensor	Date	Sensor
15/05/1979	Landsat MSS	11/08/1972	Landsat MSS	03/01/1973	Landsat MSS
07/05/1987	Landsat TM	05/08/1987	Landsat TM	10/05/1978	Landsat MSS
06/06/2001	Landsat ETM+	31/05/2001	Landsat ETM+	16/05/1983	Landsat MSS
23/07/2004[a]	ASTER	01/09/2003[a]	ASTER	07/11/1987	Landsat TM
				04/08/1990	Landsat TM
				05/02/2003[a]	Landsat ETM+

[a] Image acquired during or immediately before the MELMARINA field programs

Authority for Remote Sensing and Space Sciences (NARSS), Egypt. Where possible, the images selected for each lagoon were acquired at approximately the same time of year with spring and summer (i.e. the growing season) being preferred. The images of Merja Zerga fall within the three months between May and July whilst those for Ghar El Melh are from May to September. Images for Lake Manzala are, however, from a wider spread of months.

Image processing

Image processing, which comprised three principal steps of geometric correction, spectral enhancement and, in the case of the images of Lake Manzala, image classification was undertaken using ERDAS Imagine (v 8.7).

Geometric correction

The geometric correction of each image was carried out using standard procedures. Geometric distortions are normally introduced to satellite data during acquisition. They result from several factors including attitude (roll, pitch, and yaw), the Earth's rotation and panoramic distortions (e.g. Curran, 1985; ERDAS, 1999). The coordinates of a remotely sensed scene do not therefore correspond to a standard map projection and the coordinates of a fixed point vary from image to image. Geometric correction (rectification) is therefore necessary in order to remove geometric anomalies and create a faithful representation of the original scene by correcting pixel location errors and establishing a correspondence between ground features and their correct position throughout the image. As a result, it has the scale and projection properties (geometric integrity) of a map. Image rectification is typically accomplished on the basis of well-distributed ground control points (GCPs) located on both the images and a map of the corresponding area (Olmanson et al., 2001). For each image of the three MELMARINA primary lagoons, a number of GCPs (between 5 and 19 depending on image) were identified. These points comprised static features visible in both an image (source points) and the corresponding 1:50:000 topographic map (reference points). GCPs included road and canal intersections, bridges and other large man-made features. More natural, dynamic features such as river bends and lagoon–marine connections were not used as GCPs since they are more prone to movement between map production and image acquisition. Since both the source and corresponding reference points represented the same features with different coordinate systems, they were used to generate a transformation polynomial using the regression analysis method (Milne, 1988). A first degree polynomial transformation was considered appropriate, given the low relief of the lagoons and their surrounding landscapes. Acceptance of the transformation polynomial was based upon the root mean square (RMS) error reported between the two sets of points. The RMS errors for the transformations employed in this study were in the range 0.7–0.9 of the pixel sizes. Subsequently, the transformation polynomial was used to rectify the image to the map coordinate system using the nearest neighbour re-sampling technique (Christensen et al., 1988).

Image enhancement

Enhancement techniques are often employed in order to enhance image display properties, identify different features in an image and thereby enhance the subsequent visual interpretation. Enhancement of each of the remotely sensed images of the MELMARINA lagoons was undertaken by applying a linear stretching technique to the different spectral bands. This procedure modifies the distribution and range of digital numbers (DNs) of the image pixels so that the potentially limited range of DN values within the original image covers a larger range within the stretched image (Lillesand et al., 2008). False colour composite (FCC) images were derived in which three selected image bands were assigned to red, green and blue (R, G, B), respectively. The selection of the FCC spectral bands is usually based on the features of interest. Table 2 summarises the bands used within the false colour composite images of the MELMARINA lagoons. Although the range of wavelengths recorded in each band vary between sensors, the bands employed within the false colour composites were selected to provide as close an overlap as possible. These band combinations have been applied in similar studies (Rawan & Mars, 2001; Hewson et al., 2002).

Image classification

Review of the false colour composites of Lake Manzala (discussed below) highlighted major changes over time in the distribution of the within lake emergent vegetation, which is a characteristic feature of this particular site. The extensive islands of vegetation divide the lake into different sub-basins so that they play an important ecological role. Therefore, in order to more clearly illustrate these changes and to provide quantitative information on the relative extent of emergent vegetation compared to

open water each of the remotely sensed images of Lake Manzala were subjected to a classification procedure. This was not undertaken for the images of Merja Zerga and Ghar El Melh as emergent vegetation covers a much smaller part of both the lagoons and, as noted above, is largely restricted to marginal areas. The basic premise of multi-spectral image classification is that different surfaces have sufficiently different reflectance properties in different regions of the electromagnetic spectrum (i.e. spectral signatures). An unsupervised classification approach was adopted (e.g. Lillesand et al., 1998) in which pixels were classified based upon their spectral signatures alone without any prior knowledge of the different surfaces within the images. Classification was undertaken using image bands with the highest spatial resolution. These comprised all four bands (1–4) of the three MSS images (resolution 79 m) and bands 1–5 and 7 of the two Landsat TM and Landsat ETM+ images (resolution 30 m). The classification was restricted to a digitised lake boundary for each image identified from the false colour composites. The unsupervised classification procedure was performed using the ISODATA ('Iterative Self-Organising Data Analysis Technique') algorithm within ERDAS Imagine with an initial specified 15 arbitrary classes. This algorithm repeatedly performs an entire classification from which clusters of pixels with similar spectral signatures are identified. A minimum spectral distance formula is used to define these clusters (e.g. Calvo et al., 2003; Müllerová, 2005). After initial unsupervised classification, classes were combined based upon knowledge of the characteristics of the site to provide three major classes of open water, emergent vegetation and dry land. Although cloud cover was not significant in the majority of the images, conspicuous clouds were evident over the northeastern corner of Lake Manzala in the 1983 image. Comparisons with the preceding and proceeding images (1978 and 1987, respectively)

Table 2 Bands used in the false colour composite images of the three MELMARINA primary lagoons

RGB	Landsat ETM+		Landsat TM		Landsat MSS		ASTER	
	Band	Wavelengths (μm)	Band	Wavelengths (μm)	Band	Wavelengths (μm)	Band	Wavelengths (μm)
R	4	0.77–0.90	4	0.76–0.90	4	0.70–0.80	3	0.76–0.86
G	3	0.63–0.69	3	0.63–0.69	3	0.60–0.70	2	0.63–0.69
B	2	0.52–0.60	2	0.52–0.60	1	0.50–0.60	1	0.52–0.60

enabled a reclassification of cloud covered pixels to one of the three major classification classes. In most cases, pixels were reclassified as water. The images from 1978 and 1987 show very little change over this period in this particular part of the lake. Subsequently, the area and percentage cover of each of the classes were evaluated for each image. Seasonal changes in vegetation within Lake Manzala are relatively smaller due to the relative constancy of the climate whilst the small tidal range (e.g. Thompson et al., 2009) exerts a minimal effect on the extent of open water within the lake. Therefore, changes in
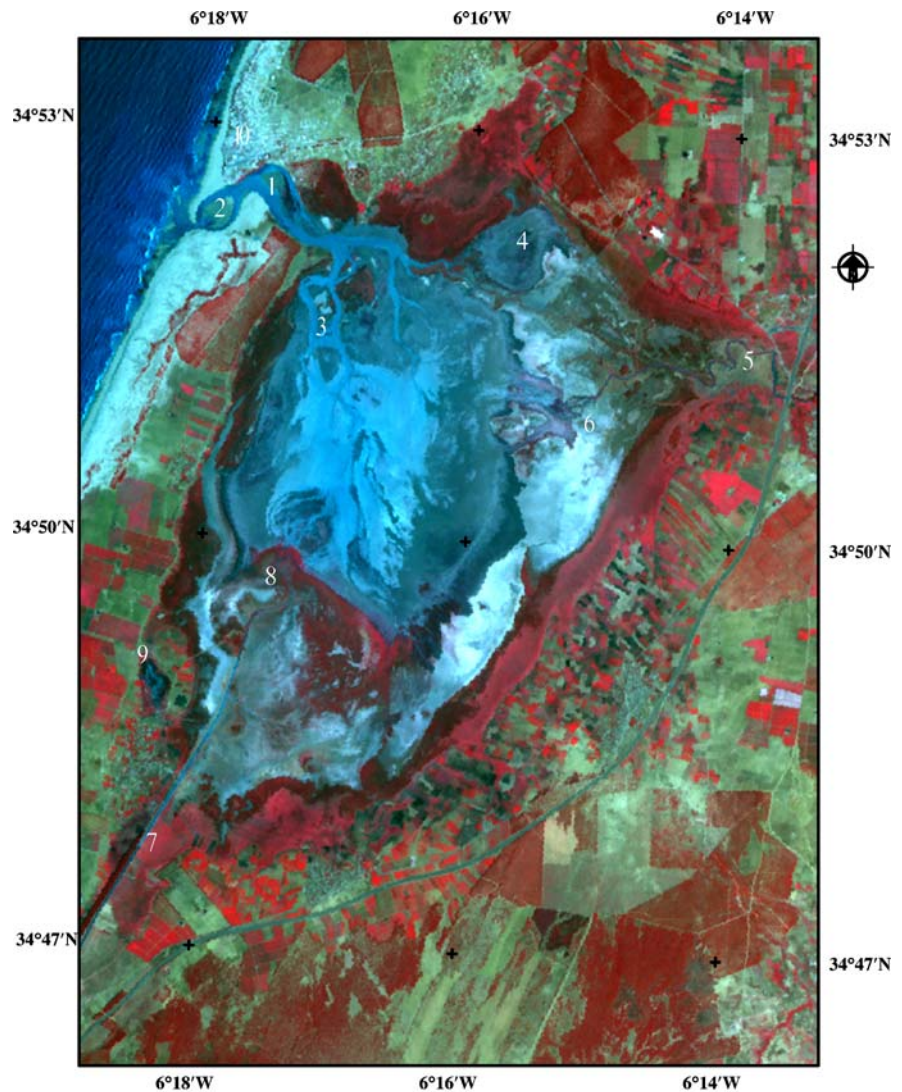
the three land cover classes are assumed to be the result of persistent trends in lake development.

Results

Recent remotely sensed imagery for each lagoon

The most recent remotely sensed images of the three MELMARINA primary lagoons (Figs. 2, 3, 4) enable the identification of some of the key features within these environments and in their immediate
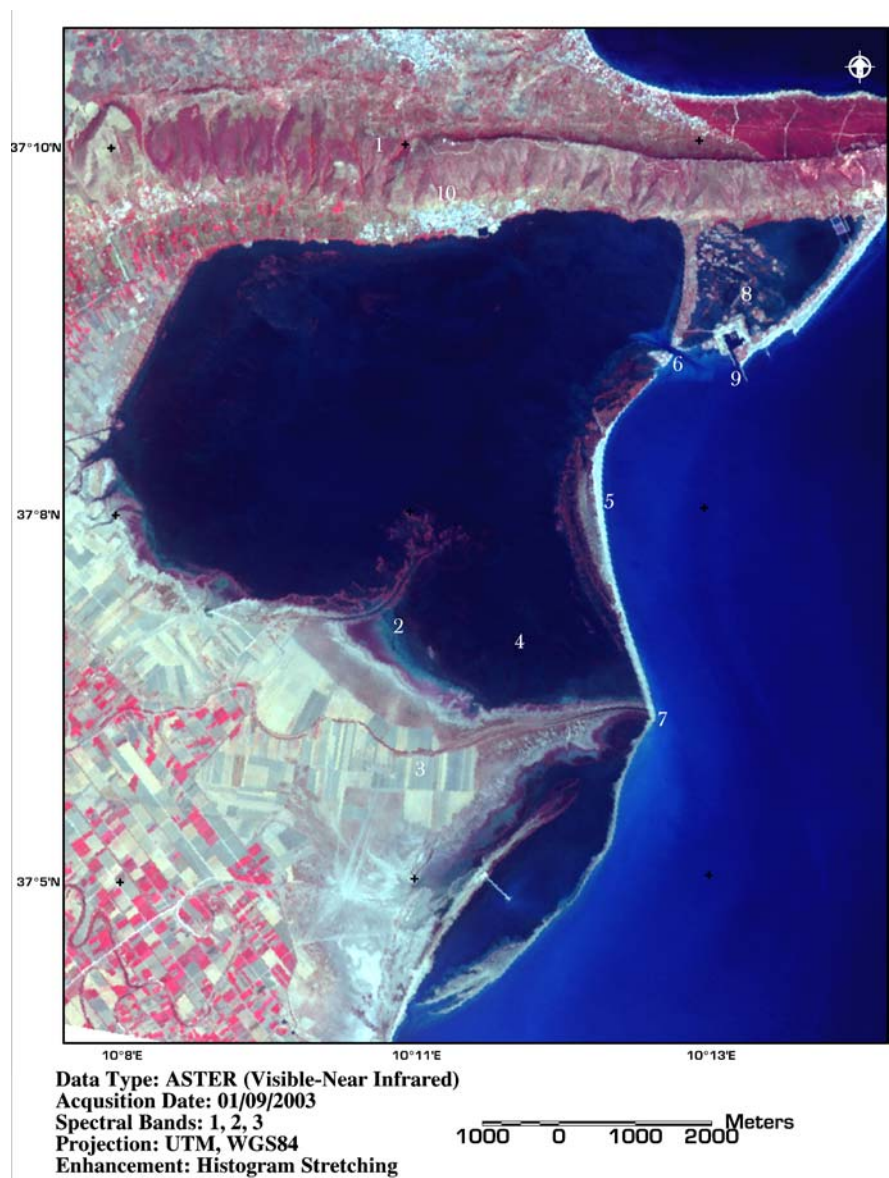

Fig. 2 False colour composite ASTER image of Merja Zerga (23/07/2004) *Red* Band 1, *Green* Band 2, *Blue* Band 3. Specific locations discussed in the text: (1) gullet, (2) inland within the gullet, (3) major in-lagoon drainage channels, (4) Merja Kahla, (5) Drader River, (6) Drader delta distibutaries, (7) Nador Canal, (8) Nador Delta, (9) Dayet Roureg, (10) Moulay Bou Selham

Data Type: ASTER (Visible-Near Infrared)
Acqusition Date: 23/07/2004
Spectral Bands: 1, 2, 3
Projection: UTM, WGS84
Enhancement: Histogram Stretching

Fig. 3 False colour composite ASTER image of Ghar El Melh (01/09/2003) *Red* Band 1, *Green* Band 2, *Blue* Band 3. Specific locations discussed in the text: (1) Jbel Nadhour, (2) old Mejerda delta, (3) former Mejerda channel, (4) Sebkht El Ouafi, (5) coastal sand bar, (6) dredged channel, (7) former mouth of Mejerda River, (8) Sebkhat Sidi Ali El Mekki, (9) new port, (10) Ghar El Melh town
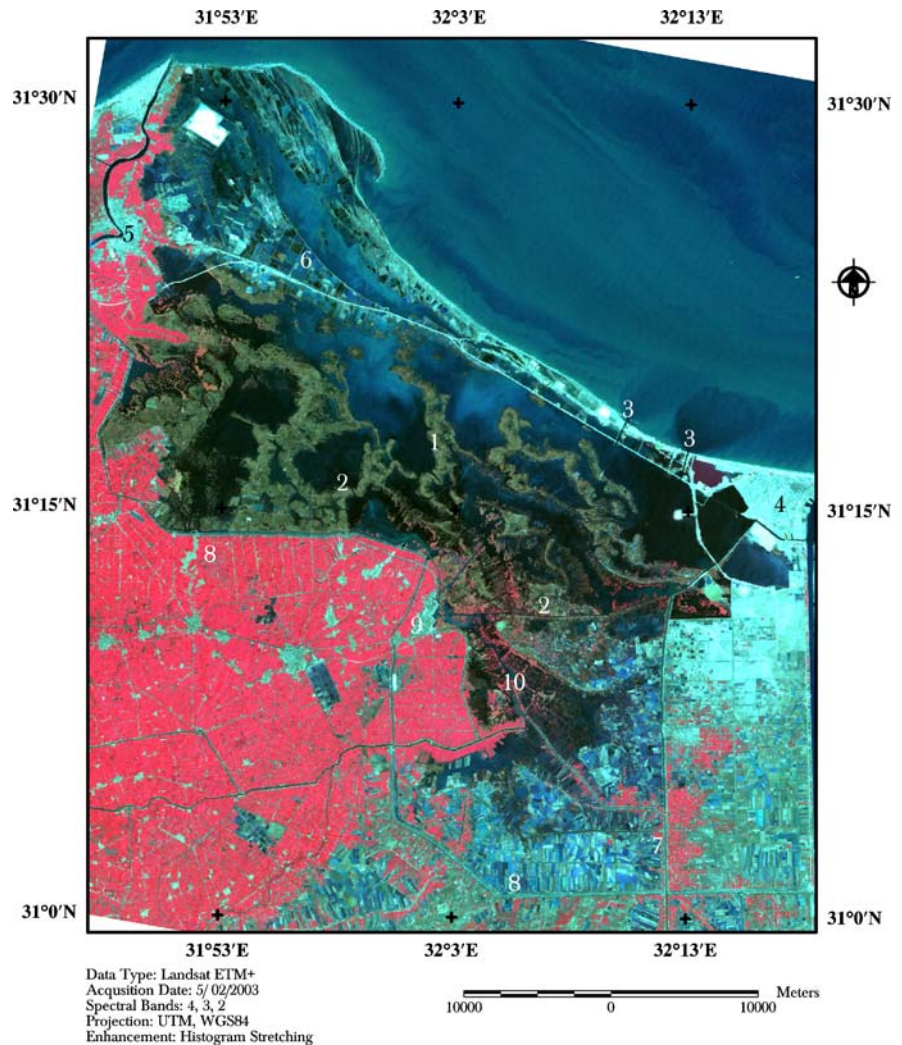

Data Type: ASTER (Visible-Near Infrared)
Acquisition Date: 01/09/2003
Spectral Bands: 1, 2, 3
Projection: UTM, WGS84
Enhancement: Histogram Stretching

surroundings at the time of image acquisition. Specific areas discussed in the text are labelled within the images.

Merja Zerga

Figure 2 provides a false colour composite image of the ASTER data acquired for Merja Zerga on 23/07/2004. Within the image, red can be broadly classified as vegetation, green as dry bare surfaces and blue as predominantly either water or wet surfaces. A number of the characteristic features of Merja Zerga

are clearly evident within the image. The relatively deep water channel (known as the "gullet"), which links the lagoon with the Atlantic Ocean, is shown cutting through the coastal sand dunes (1). The channel, which varies from 60 to 300 m in width, has variable bathymetry up to 3 m depth. An island feature within the channel at its Atlantic end (2) is visible within Fig. 2 suggesting that the image was acquired near low tide. As noted in Ayache et al. (2009), the seaward section of this channel was regularly blocked in the past by moving coastal sand bars although, more recently, the "gullet" has been

Fig. 4 False colour composite Landsat ETM+ image of Lake Manzala (05/02/2003) *Red* Band 4, *Green* Band 3, *Blue* Band 2. Specific locations discussed in the text: (1) vegetated islands, (2) channels cut through islands, (3)El Gamil channels, (4) Port Said, (5) Damietta, (6) intensive fish farms, (7)Bahr El-Baqar drain, (8) El Salem Canal, (9) Matariya, (10) fish farms

Data Type: Landsat ETM+
Acquisition Date: 5/02/2003
Spectral Bands: 4, 3, 2
Projection: UTM, WGS84
Enhancement: Histogram Stretching

actively managed in order to maintain marine connectivity. The southward extending sand bar at the end of the "gullet" as well as the southward deflection of the channel itself suggests that the predominant direction of the alongshore sediment transport is north–south.

Drainage channels in Merja Zerga, which extend from the "gullet" towards the centre of the lagoon, are clearly distinguishable. Two major channels run due south along the western edge of the lagoon towards the less shallow central area (3) (Ayache et al., 2009; Thompson et al., 2009). Another major channel initially runs east–west from the "gullet" also before being diverted to the south and splitting into two branches. The channel which at high spring tides links Merja Zerga with the smaller wetland area

of Merja Kahla (4) to the north of the main lagoon (Ayache et al., 2009) is also clearly visible. The centre of the lagoon, indicated in light blue within Fig. 2, retains no or only a few centimetres of water at low tide. Its irregular shape is indicative of the complex bathymetric characteristics of the lagoon depression. These reflect the drainage features on the inter-tidal mudflats, which extend from the centre of the lagoon towards the marginal areas. On these mudflats, areas indicated in darker blue within Fig. 2 denote the presence of shallow standing water or drainage channels.

Figure 2 shows the two major depositional features within Merja Zerga, which are associated with freshwater inflows. The deltaic feature at the end of the Drader River, which can be seen meandering

towards the lagoon from the east, is clearly visible (5). One primary channel crosses the delta before splitting into four main distributaries (6). Elsewhere, dry channels and former drainage across the delta are indicated by the presence of linear-vegetated features (typified mainly by *Juncus*). The most notable of these is associated with the levee which separates Merja Kahla from the main body of the lagoon. Since the ASTER image was acquired in July, when flows within the Drader River are very low and made up almost entirely of irrigation return flows (e.g. Ayache et al., 2009; Thompson et al., 2009), water appears to be restricted to the main channel. It is, however, possible that during winter floods, water spills into other channels and even across the surface of the delta. The lower reaches of the delta (the light blue and white areas in Fig. 2) have little vegetation except for algae and some patches of *Arthrocnemum*. These extensive mudflats are inundated by spring tides. The upper, higher elevation areas are shown to be extensively vegetated with field surveys (undertaken in 2003) showing that the dominant species were *Juncus maritimus* and *J. acutus*.

The much straighter course of the Nador Canal can be identified in Fig. 2 entering the lagoon from the south (7). It has also created an extensive prograding deltaic depositional structure (8). Unlike the delta of the Drader River, the most downstream parts of the Nador Canal's delta are shown to be densely vegetated. This could suggest that they are at a higher elevation permitting the colonisation by *Juncus* and some *Phragmites* which characterises the margins of the canal. The land lateral to the Nador delta is a sparsely vegetated mudflat. Grasses (*Spartina* and *Panicum*) together with *Arthrocnemum* are common on the western side whilst isolated stands of *Phragmites* and *Typha* and widespread *Arthrocnemum* occur on the eastern side. In contrast, in the upstream of the Nador Canal delta, the vegetation gives way to grazed grassland on the eastern side and *Eucalyptus* groves and agriculture on the western side. The small (c. 0.1 km^2) shallow wetland area, Dayet Roureg (9), to the west of the canal is also clearly indicated in Fig. 2 as an area of open water fringed by (*Juncus*) vegetation. Generally, marginal vegetation of *Juncus* characterises much of the edge of Merja Zerga beyond the mudflats. In particular, Fig. 2 indicates wide bands of vegetation along the shores between the deltas of the Drader River and the

Nador Canal. Ayache et al. (2009) reports on the vegetation in these areas beyond the *Juncus* zone; a belt of heavily grazed often water-logged grassland is particularly extensive on the eastern border of the lagoon, beyond which lies predominantly cultivated land. Individual fields in this area, as well as to the immediate north of the lagoon, are clearly evident within Fig. 2. Figure 2 also illustrates the presence of vegetation on the coastal dunes (beyond the darker red-coloured *Juncus* zone) to the west of the lagoon. The largest of these vegetated areas are plantations of *Eucalyptus* and *Acacia*, which were planted in the early 1970s, (Ayache et al., 2009) although there are also some smaller areas of agriculture as indicated by the rectangular field outlines. The linear vegetated features on the dunes mark cactus hedge tracks. The largest settlement in the area, Moulay Bou Selham (10), is visible to the immediate north of the "gullet". Similarly, the smaller villages of Ouled Mesbah (to the south of the Dayet Roureg wetland) and Merhitene (south of the lagoon and adjacent to the motorway which is also clearly visible) are also distinguishable within the image.

Ghar El Melh

Figure 3 provides a false colour composite of the most recent (01/09/2003) image available for Ghar El Melh. It shows that the boundary between the lagoon and the surrounding landscape is much more distinct than it is for Merja Zerga. This is especially so in the north where the scrub covered hills of the Jbel Nadhour (1) provide a structural limit to the lagoon (see Ayache et al., 2009). The low tidal range of the Mediterranean ensures that within the lagoon the tidally induced fluctuations in water levels are very small (0.13–0.07 m; Thompson et al., 2009). This consequentially accounts for the lack of extensive inter-tidal habitats within the remotely sensed image of Ghar El Melh. Unlike Merja Zerga, the bathymetry of this lagoon is relatively uniform with most areas being between 1.0 and 1.5 m deep (Thompson et al., 2009). With the exception of the old delta of the Mejerda River (2) and the area immediately adjacent to the coastal sand bar little bathymetric information is shown within Fig. 3, but some turbidity features are indicated.

The former delta of the Mejerda is clearly visible in the south indicating the location where the river

discharged into the lagoon before its diversion to the south during a major flood at the end of the nineteenth century (Ayache et al., 2009). The channel into which the river shifted can be seen to the south of Ghar El Melh (3) although it is now largely dry following another flood in 1973, which resulted in the river moving 10 km to the south. Within Ghar El Melh, the former channel can be distinguished as a linear feature extending approximately 1.7 km into the lagoon between what are assumed to be shallower areas made up of historic levees. The shallower water in these areas encourages the growth of vegetation that was shown in field surveys to be dominated by sparse *Arthrocnemum* and abundant benthic algae. Further into the lagoon, former delta distributaries are suggested by the widening of the area of shallow water. Ayache et al. (2009) suggest that the delta (now partly eroded) was once more extensive with one branch extending towards the coastal sand bars and, in the first half of the twentieth century, effectively isolating a small southern lagoon basin (Sebkhet El Ouafi, 4). The gently shelving lagoon margin in the vicinity of the delta, which is indicated by the progressively darker blue from the lagoon shore towards the lagoon's centre, provides for some marginal plants including benthic macro-algae and fringing *Arthrocnemum*. These can extend up to 100 m into the lagoon. The benthic macro-algae (*Enteromorpha* and *Ulva*) are particularly abundant on the north shore of the lagoon as indicated by a thin red marginal band in Fig. 3 and probably results from excessive nutrient pollution (Ayache et al., 2009). Vegetation is also present on the lagoon side of the sand bar which separates Ghar El Melh from the Mediterranean (5). This gently shelving shore is consistent with the seaward movement of the sand bars over the last century which is described by Ayache et al. (2009) and discussed below. The dredged channel towards the northern end of the sand bar is clearly distinguished in Fig. 3 (6). To the immediate south of this channel, one of the low-lying sections of the bar which provides ephemeral marine connectivity during periods of high tide or major flood events is visible. Impacts of the diversion of the Mejerda River upon coastal processes are also clearly demonstrated in Fig. 3. The former mouth of the river (7) has been blocked by the sand bar as a result of the north–south alongshore currents. This has, in turn, created a smaller coastal lagoon south of Ghar El Melh.

The distinct sub-lagoon of Sebkhat Sidi Ali El Mekki in the northeast (8) is shown to contain a series of small vegetated islands which are probably former sand bars composed of sediment derived from the Jbel Nadhour (Ayache et al., 2009). This basin was effectively cut off from the main Ghar El Melh lagoon due to the stabilisation of the sand bar along its western margin to enable the construction of a road. This was undertaken in the early 1970s to provide access to a new port built for sea going vessels (9). Much of this sand bar has since been cultivated by local people growing fruit and vegetables within small plots which are visible within Fig. 3. The new port can be seen on the southern edge of the Sebkhat Sidi Ali El Mekki as can the jetties constructed to prevent blockage of the port's mouth. The build up of sand to the north of the jetties further indicates the north–south direction of alongshore sand transport. The entrapment of this sand may have long-term implications for Ghar El Melh's main sand bar. For example, it is evident in Fig. 3 that the most northerly section of the sand bar, adjacent to the dredged channel, is thinner (<50 m) than further south (c. 100 m), which might indicate its erosion in the face of reduced up-current sediment supply.

The intensive nature of the agricultural landscape around Ghar El Melh is clearly evident in Fig. 3. For example, to the west of the Ghar El Melh town (which, along with its port, is visible on the northern shore of the lagoon, 10) the numerous rectangular areas of vegetation correspond to small agricultural plots that extend almost to the lagoon's shore. The intensively cultivated Utica floodplain lies to the south and west of Ghar El Melh. The complex irrigation and drainage infrastructure in this area necessitates larger field sizes than those to the immediate north of the lagoon. Since the image was acquired in September, after many crops had been harvested, a large number of the fields in this area are shown to lack vegetation.

Lake Manzala

Figure 4 shows a false colour composite of the Landsat ETM image of Lake Manzala acquired on 05/02/2003. As in Figs. 2 and 3, red can be broadly classified as vegetation, green as dry bare surfaces and blue as predominantly either water or wet surfaces. The image demonstrates that Lake Manzala

is very different from the other two MELMARINA primary lagoons. The lake is substantially larger presently covering around 700 km^2 compared to c. 13 and c. 36 km^2 for Merja Zerga and Ghar El Melh, respectively. Unlike these other two lagoons, Lake Manzala is divided into a series of sub-basins which are delineated by numerous vegetated islands dominated by *Phragmites* and *Typha*. These islands are clearly distinguished in Fig. 4 and are coloured red-brown (1). They comprise a mixture of dry land just above the lake water surface and fringing emergent vegetation. It has been suggested that those islands in the north with long axes roughly parallel to the coast are former coastal sand ridges whist further south those which trend in a more north–south direction are remnants of deposition along former branches of the Nile (Sestini, 1976; Abdel-Kader, 1982; Randazzo et al., 1998). The islands within the lake influence circulation patterns and each of the different sub-basins consequentially have different hydrochemical and sedimentological characteristics (Tennessee Valley Authority, 1997). In a number of locations, channels cut through the islands to aid navigation can be identified (2). Similarly, the channels at El Gamil dredged through the coastal sand bars, which in places are 2-km wide, can also be distinguished (3) whilst, to the south, the main Nile Delta drains, which provide freshwater to the lake, are also visible.

The strong influence of human activities on Lake Manzala and its immediate surroundings is clearly evident in Fig. 4. For example, the construction of the new road running along an embankment, which can be seen from Port Said (visible on the coast on the eastern edge of the image, 4) to Damietta (located to the west on both banks of the Damietta branch of the River Nile, 5), has isolated the large northwestern sector of the lake except for a few locations when the road passes over bridges. It has also created an elongated strip of open water approximately 1-km wide between the coastal sand bars and the embankment in the east. Isolation has permitted the extensive reclamation of lake bed in the northwest of the lake for aquaculture development. The numerous rectangular divisions in this part of the lake are indicative of the widespread and largely uncoordinated construction of embankments to enclose engineered fish farms (6). These enclosures are shown in Fig. 4 to also be extending into the northwestern part of the main body of Lake Manzala from the road embankment.

In Fig. 4, the impact of reclamation can also be distinguished along the southern margins of the lake. Although in some places, the margins of the lake are relatively ill defined, such as in the southwest where the Bahr El-Baqar drain (7) discharges into the lake and open water areas are fringed by marshes dominated by *Phragmites* and *Typha* (e.g. Randazzo et al., 1998; Ramdani et al., 2001), elsewhere there is a more distinct division between the lake and dry land. This is most clearly demonstrated by the straight east–west aligned lake margin in the southwest. Here, the embankments of the El Salam Canal (8), which delivers water to the North Sinai Agricultural Development Project (NSADP, World Bank/Ministry of Public Works and Water Resources, 1992; FAO, 2005) delineate the boundary of Lake Manzala. The canal, which receives water from the Damietta Branch of the Nile and intercepts water from some of the main drains crossing the delta towards Lake Manzala, can be seen turning to the south before again heading east where it eventually passes via a siphon beneath the Suez Canal beyond the eastern edge of Fig. 4.

To the south of Lake Manzala, Fig. 4 displays an intricate field system which is characteristic of the Nile Delta. Much reclamation has occurred in this area over the last few decades and a significant part of the agricultural land to the immediate south of Lake Manzala was reclaimed from the lake. Figure 4 suggests that at the time of image acquisition most of the agricultural land to the west was under crops whilst to the east, which includes some of the most recently reclaimed land, many field systems were not cultivated. The substantial town of Matariya on the southern shore of the lake is also visible (9). Linear vegetated features within the lake are particularly dense in the lake region immediately east and north of this town and indicate the presence of extensive fish farming and associated ad hoc management of the particularly luxuriant emergent vegetation in this area (10).

Decadal scale lagoon change

The false colour composite images of the three MELMARINA primary lagoons acquired on different dates within a period of up to 30 years duration enable the identification of environmental changes at each site. These changes relate to changes in both the

lagoons and in their surrounding near landscapes. Despite varying resolution (from as small as 15 m for the recent ASTER images to 79 m for the Landsat MSS images) and differences in timing, some principal environmental change features can be discussed which augment the observations reported in Ayache et al. (2009).

Merja Zerga

The four false colour composite images of Merja Zerga are shown in Fig. 5. These include the most recent ASTER image discussed above. Significant changes in a number of specific features are discernable. Although all the images are from the three months of May–July, the large tidally induced oscillations in lagoon water level (see Thompson et al., 2009) make recognition of some within lagoon changes more difficult. Perhaps most apparent are the physical changes associated with the channel which links the lagoon with the Atlantic Ocean. A beach sand spit on the southern side of this channel is shown to be well developed in 1979. Subsequent images show that this feature diminished in size, as the channel was deflected to the south. By 2001, a prominent spit had developed on the northern side of the channel and, as discussed above, an island of sand had accumulated in the channel's mouth by 2004. Also clearly shown in Fig. 5 is the extension into Merja Zerga of the delta of the Nador Canal. The

Fig. 5 False colour composite images of Merja Zerga (**a**) 15/05/1979, Landsat MSS; (**b**) 07/05/1987, Landsat TM; (**c**) 06/06/2001, Landsat ETM+; (**d**) 23/07/2004, ASTER
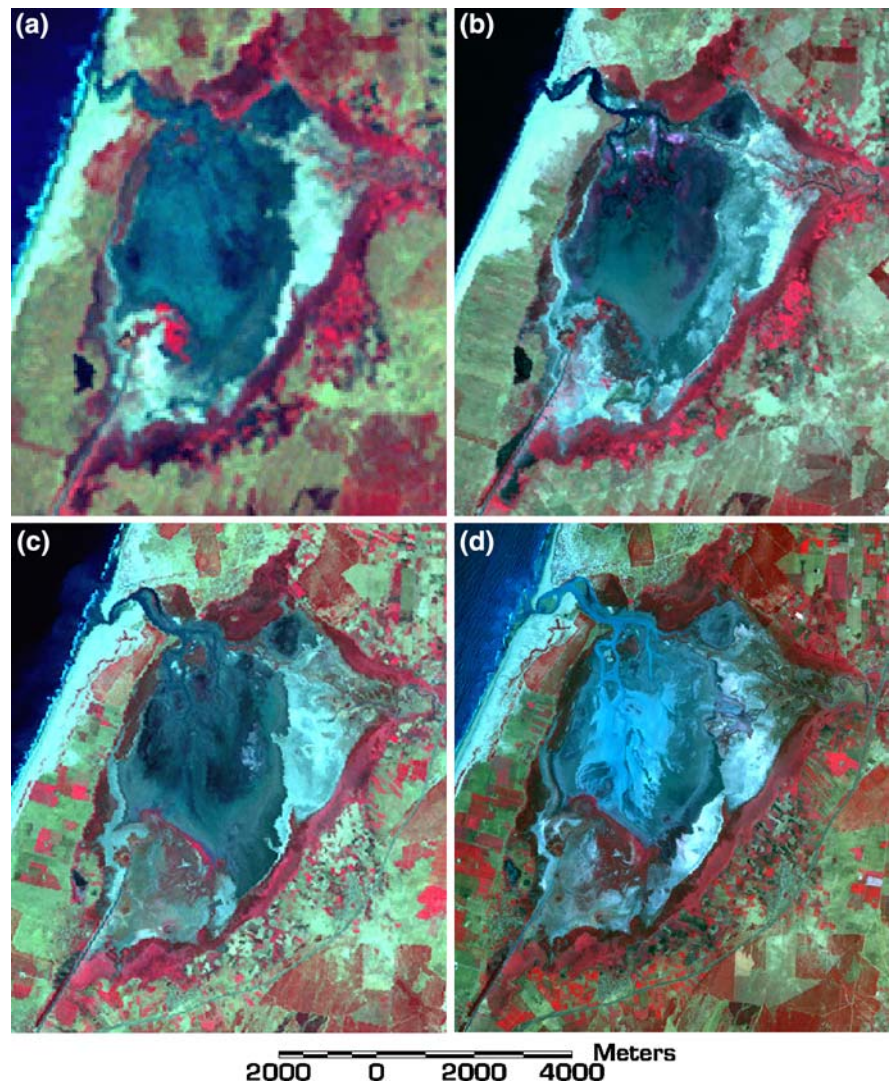
eastern side of the delta appears to have experienced considerable infilling with a commensurate increase in salt marsh vegetation cover. The 1979 image suggests that deposition has previously been concentrated in the west locally raising surface elevations and permitting the colonisation by vegetation probably dominated by *Juncus* and *Phragmites*. By 1987, the vegetation had expanded by approximately 1 km to the east, a process which appears to have continued towards the present day. The delta–lagoon margin is now much straighter than it was in the late 1970s. In the northeast, sediment from the Drader River has accumulated in both westerly and southwesterly directions. The expansion of the Drader's delta in a westerly direction has effectively closed off the northerly Merja Kahla sub-basin. Whilst in the 1979 image, a nearly continuous 600-m long connection with the main lagoon along the southern edge of the smaller body of water is discernable, over time this has closed so that within the 2004 image connection is limited to the previously discussed vegetation (*Juncus*) fringed channel extending to the proximal section of the "gullet". Beyond the lagoon, the sequence of images in Fig. 5 clearly show the intensification of agriculture in the adjacent landscape. The development of field systems on the gently sloping ground to the east of Merja Zerga can be identified. In 1979, very little vegetation is indicated on the dunes that lie to the west of the lagoon. By contrast, in 2001, large parts of the dunes are covered in rectangular shaped fields, which in turn appear to have increased in number and extent four years later. Flower et al. (1992) suggested that Dayet Roureg, the small wetland to the west of the Nador Canal, had experienced recent rapid siltation. This could be attributable to its location near the canal or enhanced agricultural activity in the surrounding area. Figure 5 shows that in both the 1979 and 1987 images, the wetland can be clearly distinguished as a dark area of open water. The more recent images suggest a potential reduction in its extent as well as colonisation by fringing vegetation, reported above to be dominated by *Juncus*. This would be consistent with the infilling of the wetland by sediment.

Ghar El Melh

Figure 6 provides the four false colour composite images, including the previously discussed ASTER image, available for Ghar El Melh. Probably, the most marked changes recorded in the years between 1972 and 2003 are associated with the geomorphological development of the sand bar which delimits the lagoon from the Bay of Tunis and the southern extension of this bar beyond the old Mejerda River mouth. Over time, the sand bar has straightened as its central sections have migrated to the east. The central part of the bar moved by as much as 320 m between 1972 and 2003 resulting in an increase in the combined area of the main lagoon and Sebkhet El Ouafi of nearly 4 km^2 (30.70 km^2 in 1972 and 34.65 km^2 in 2003). Ayache et al. (2009) provides evidence from historical maps which suggest that this process, so clearly evident in Fig. 6, characterised much of the twentieth century development of the lagoon. As the sand bar has become less concave in the south of the lagoon, the southerly alongshore currents have become less diverted out to sea as they cross the former mouth of the Mejerda River. As a result, the sand spit which has developed in this area has migrated inland almost completely isolating a body of coastal water creating another lagoonal environment. However, at times, as indicated in the 2001 image, low lying parts of this sand bar provide connections between this lagoon and the sea. Further north, another change affecting the coastal sand bars has been the construction of the new port. In 1972, the coastal sand bars were uninterrupted between the Jbel Nadhour in the north and the former Mejerda mouth in the south. Within the 1987 image, a sharp change in the shape of the sand bars including an increase in their width can be identified around the new port. Other features of the coastal sand bar include changes in the channels which cross it and link the lagoon with the sea. The images from 1972 and 1987 suggest that the main lagoon–sea connections were towards the central, most concave parts of the sand bar. By 2001, these connections are no longer visible and instead the major lagoon–sea connectivity is provided by the dredged channel to the immediate south of the new port. Within the lagoon, the former delta of the Mejerda appears to show little change since 1972. This suggests that its rate of erosion has declined from that experienced in the first half of the twentieth century when the delta effectively isolated the southern part of the lagoon. Ghar El Melh town on the northern shore has grown
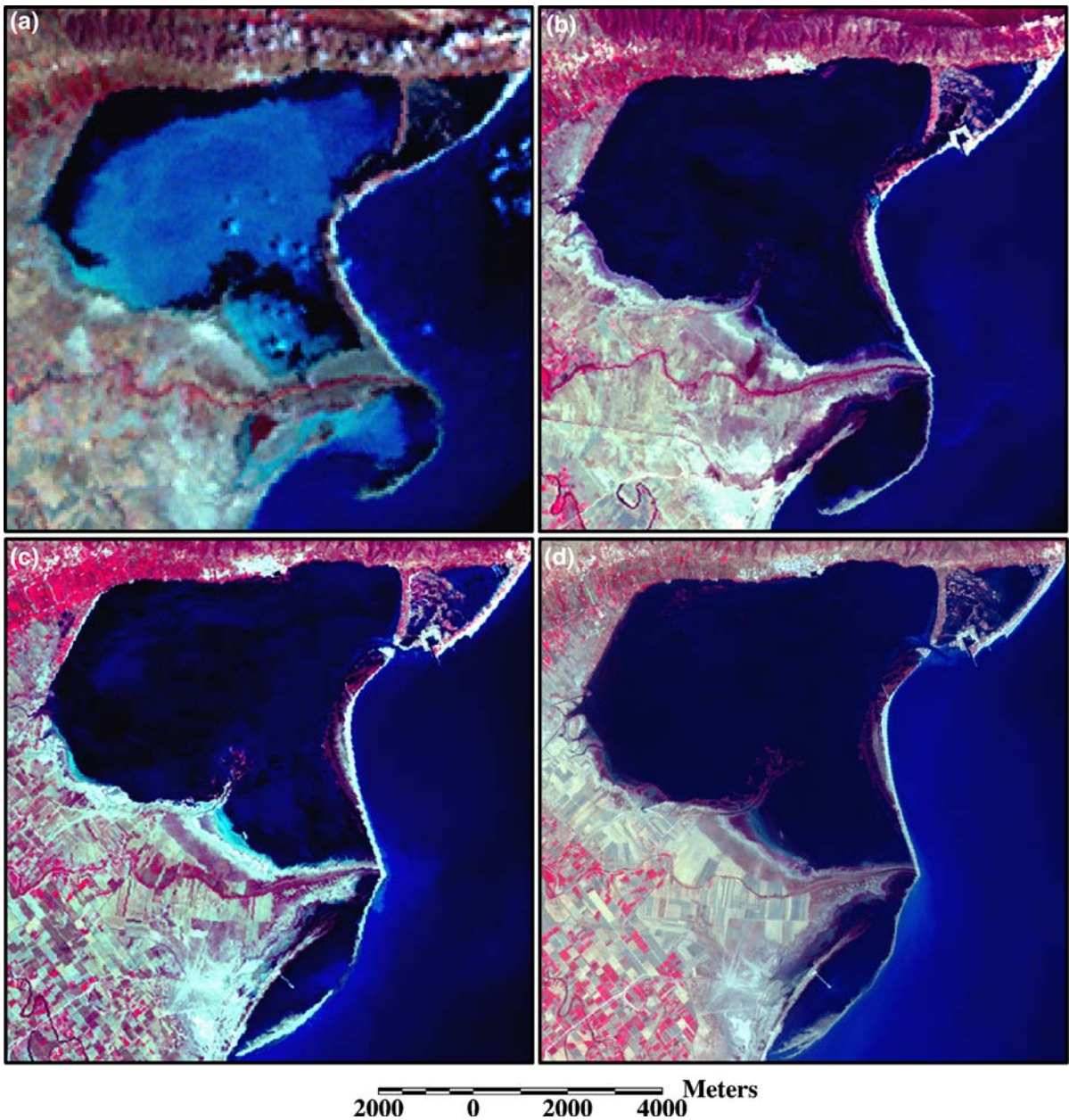
Fig. 6 False colour composite images of Ghar El Melh (**a**) 11/08/1972, Landsat MSS; (**b**) 05/08/1987, Landsat TM; (**c**) 31/05/2001, Landsat ETM+; (**d**) 01/09/2003, ASTER

between 1972 and 2003 with development being concentrated in the west.

Lake Manzala

The six false colour composite images for Lake Manzala, including the 2003 Landsat ETM+ image previously discussed, are shown in Fig. 7. Due to the

much larger extent of this lake compared to the other two MELMARINA primary lagoons, Fig. 8 provides details from the same areas within the earliest and latest images to illustrate the specific changes which can be identified. The most marked changes within the lake concern the extent of open water and the development of islands of emergent vegetation. In the 1973 image, this vegetation is largely restricted to

Fig. 7 False colour composite images of Lake Manzala (**a**) 03/01/1973, Landsat MSS; (**b**) 10/05/1978, Landsat MSS; (**c**) 316/05/1983, Landsat MSS; (**d**) 07/11/1987, Landsat TM; (**e**) 04/08/1990, Landsat TM; (**f**) 05/02/2003, Landsat ETM+ (*boxes* indicate location of insets on Fig. 8)
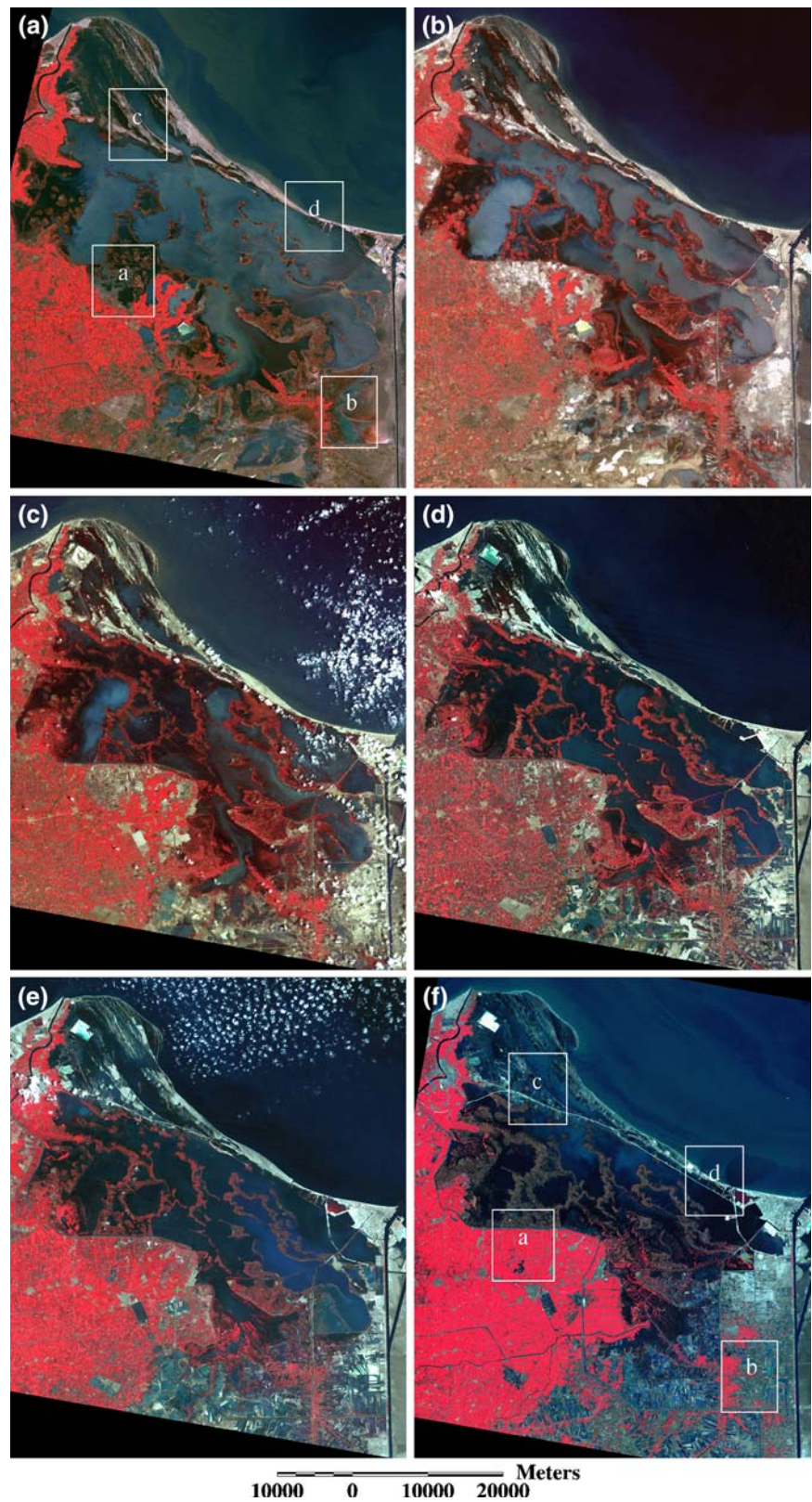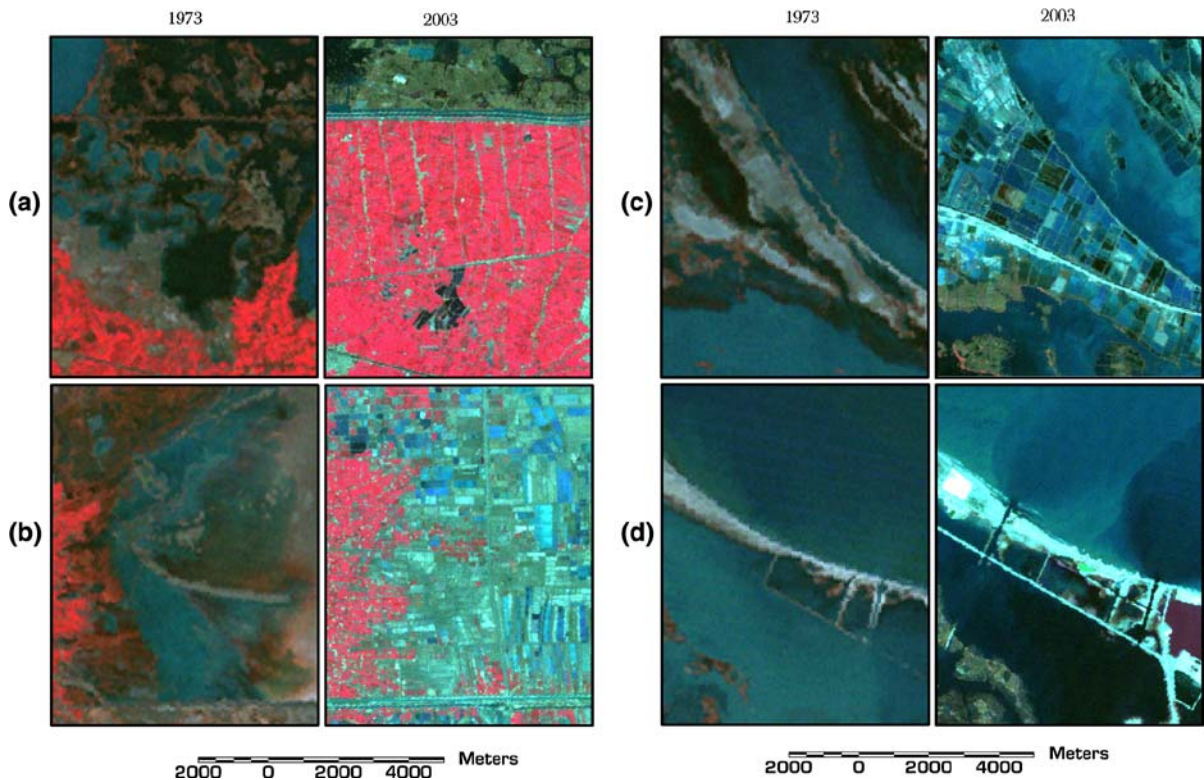
Fig. 8 Sections of the oldest (03/01/1973, Landsat MSS) and most recent (05/02/2003, Landsat ETM+) false colour composites of Lake Manzala. Locations of insets are indicated on Fig. 7. (**a**) Southwestern lake margin showing impact of Salam Canal; (**b**) lake bed reclamation to the east of the Bahr El Baqar drain, (**c**) northwest corner of the lake before road construction and reclamation for fish farms; (**d**) northeast section of the lake including new embankments and engineered marine connections

the western and southern sectors of the lake with several irregular strips of vegetation in the central area. Within 10 years (1983) this vegetation had expanded dividing the lake into the sub-basins which now characterise Lake Manzala. In contrast, the spatial pattern of the vegetated islands within the main body of the lake changed relatively little in the following 20 years (1983 compared to 2003). These changes are further demonstrated in Fig. 9, which shows the results of the classification of Lake Manzala into the three land cover classes of open water, vegetation and bare land. The concentration of large areas of wetland vegetation in 1973 within the southern part of the lake is clearly demonstrated. Within the main body of the lake, vegetation is concentrated in thin linear bands which are shown to have increased in width by 1978. This process continued till 1983 with patches of vegetation coalescing. Over the next 20 years, the boundaries of these sub-basins were retained.

Major changes have occurred around the margins of the lake, including the vegetation in these areas, since the early 1970s. Perhaps, the most profound has resulted from the construction of the El Salam Canal which, as described above, now runs eastward along the southwestern margin of the lake. In 1973, the lake margin in this area was relatively ill defined with open water giving way to emergent vegetation before agricultural land further south (Figs. 7, 8a). By 1983, the engineering work associated with the canal had shifted the lagoon's margin by as much as 6 km to the north in some locations. Figure 7 shows that the land reclaimed from the lake to the south of the canal was rapidly converted to agricultural production. As indicated above, large areas in the southeastern parts of the lake have similarly been reclaimed. For example, a large wetland area to the east of the Bahr El Baqar drain has been reclaimed since 1990 and is now (2003) partly under agriculture (Fig. 8b). The

Water
Vegetation
Land
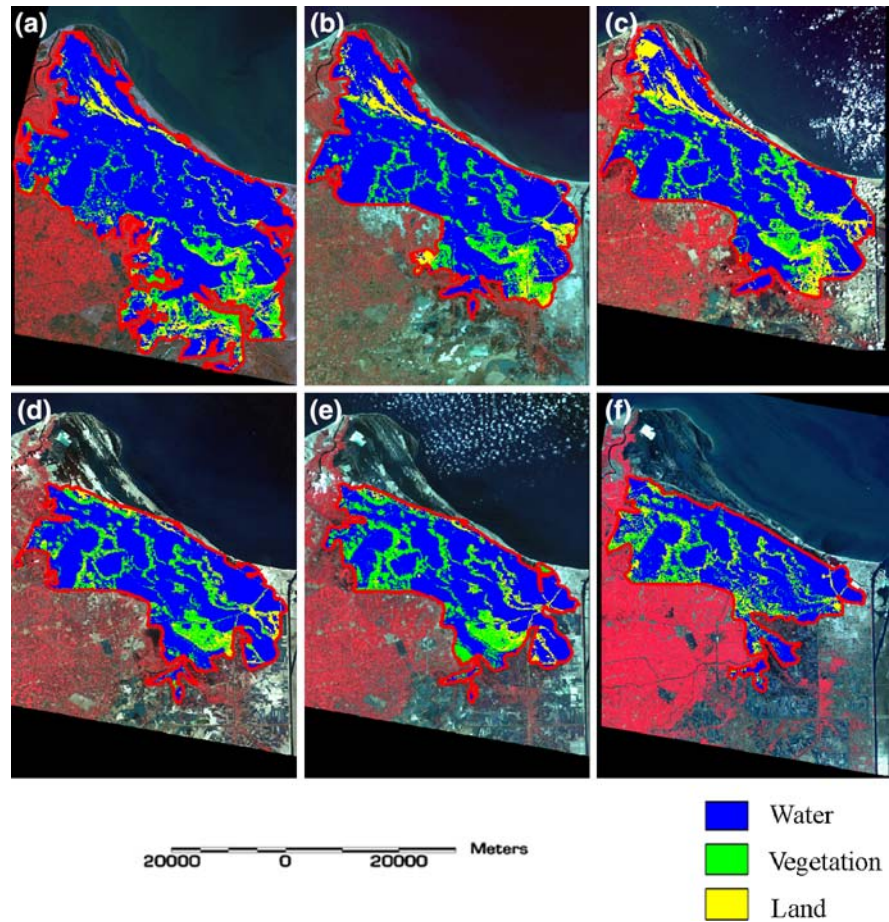
isolation of the northwestern part of Lake Manzala from the main lake is illustrated in Fig. 7. The earliest images show that although a wide unvegetated bar, probably a former coastal sand ridge, ran along the southern margin of the roughly triangular section of the lake, there were numerous relatively wide connections between it and the main lake. Construction of the road linking Port Said to Damietta began in 1990 with the work being completed by 2000. This road is shown to have been constructed on the top of the sand bar in the most recent image. Many of the connections between these two different parts of the lake have therefore been lost. Improved access to this part of the lake due to the new road is probably a major factor in the conversion of extensive areas of lake bed to fish farming. Figure 8c shows that this process has resulted in major changes in this part of the lake. The northeastern section of the lake has been under development since the 1970s with the construction of embankments associated with

transport and waste water control for the Port Said area together with the sluice gates on the two main marine channels (Fig. 8d).

Table 3 demonstrates that the combined impact of the activities discussed above has been a substantial decline in the overall area of the lake from more than 1,400 km^2 in the early 1970s to less than 700 km^2 in 2003. This decline in lake area should be considered when interpreting the relative importance of the land cover classes shown in Table 3. For example, the total area of vegetation has declined consistently since 1973 (with the exception of 1990), so that its total extent in 2003 was almost 50% of that in 1973. However, due to the decline in the total lake area, the percentage cover of vegetation has remained relatively stable although showing a small increase in the late 1980s/early 1990s. Similarly, the proportions of both water and land have remained very approximately the same over the period 1973–2003 (Table 3).

Table 3 Area and percentage of the total classified area of three land cover classes within Lake Manzala: 1973–2003

Image	Area (km^2)				Percentage of classified area		
	Water	Vegetation	Land	Total	Water	Vegetation	Land
03/01/1973	1070	243	128	1441	74.3	16.9	8.9
10/05/1978	819	191	86	1096	74.7	17.4	7.8
16/05/1983	709	165	151	1025	69.1	16.1	14.8
07/11/1987	580	164	65	809	71.7	20.3	8.0
04/08/1990	520	190	57	767	67.8	24.8	7.4
05/02/2003	491	125	63	679	72.3	18.4	9.3

Discussion

The application of remote sensing techniques to landscape characterisation, habitat monitoring and spatial analysis of surface cover change has made major advances in the past three decades (e.g. Schowengerdt, 2007). However, the use of simple remote sensing techniques are still relatively under-used in ecology and particularly in hydrobiology and wetland systems within less developed regions. Here, they have particular relevance to informing environmental management. This study has utilised remotely sensed data in a comparative way in the assessment of three coastal lagoons in North Africa.

Here, some of the principal attributes of remote sensing, including spatial coverage, availability of archives of historic imagery and relative cost effectiveness compared to field programmes, make it an attractive option for mapping and monitoring. The relatively large size of many North African coastal lagoons, especially Lake Manzala, means that whole site ground surveys cannot be undertaken easily and repeatedly. Furthermore, extensive areas of shallow water mean that boat access is hindered whilst the large tidal regime of sites such as Merja Zerga means that access to many areas is limited to high tide. When coupled with the frequently fine cloudless weather in North Africa, remotely sensed data combined with appropriate targeted ground survey can provide uniquely detailed spatial information on surface features across entire wetland landscapes. Comparison of images from different dates over the last few decades provides a means of assessing the changes in site characteristics including near landscape geomorphology, lagoon hydromorphology and the distribution of aquatic and marginal vegetation. Although the first available satellite information from

sensors such as Landsat MSS has been used successfully for large wetlands (Hardisky et al., 1986), its use is more limited for small scale studies (e.g. vegetation community identification and mapping) within wetlands. These environments, such as the MELMARINA primary lagoons, are typically spatially diverse and exhibit complex communities of aquatic vegetation as well as wide variations in water quality within relatively small areas. Higher resolution such as Landsat TM, Landsat ETM+ and ASTER enable the discrimination of smaller areas within these environments (Turner et al., 2003; De Roeck et al., 2008).

Contemporary status of the coastal lagoons

Within this study, the spatial features of each of the three MELMARINA primary lagoons were identified using a variety of satellite data (Landsat MSS, TM, ETM+ and ASTER, cf. Table 1) following appropriate image processing and (for Lake Manzala) classification. The false colour composite images of the three lagoons capture the major biogeographical features. The large tidal cycle at Merja Zerga is a complicating factor that affects the spatial analysis since the extent of the exposed mudflats beyond the fringing *Juncus* communities varies substantially according to water levels and hence the time of image acquisition. Extensive fringing salt marsh communities are largely absent at the other two sites where tidal fluctuations are small and where water margins are less variable and more easily delineated. Contemporary images of all three lagoons display the geomorphological characteristics of the sandy bars, spits and dunes that separate them from the sea. Only at Merja Zerga is some agriculture developed on the very substantial coastal dune strip but elsewhere land

surrounding each lagoon is intensively cultivated and field systems encroach almost to the water margins of Ghar El Melh and Lake Manzala.

Within-lagoon vegetation at Merja Zerga or Ghar El Melh is characterised by submerged communities that are exposed during low tide only at the first of these two sites. The relatively low density of this benthic aquatic vegetation compared to the dense stands of emergent vegetation at Lake Manzala resulted in less clear discrimination within the satellite images although the FCC images do indicate the fringing vegetation (*Juncus* and/or green macro-algae, see Ramdani et al., 2001). The situation in Lake Manzala is very different and this site is characterised by the presence of more than 1,000 small irregular islands, which consists of clay, sand or mollusc shells. These island range up to several square kilometres in area and many are densely vegetated (Zahran et al., 1988, 1990). An extensive community of emergent vegetation (mainly *Phragmites* and *Typha*) occurs on and around these islands. These vegetated areas are clearly distinguished within the satellite image. Thus, the extent of emergent vegetation within the lake is well captured by the satellite image as are the linear navigation channels which pass through the vegetation and between the islands. Floating plants, particularly water hyacinth (*Eichhorina crassipes* as well as *Azolla* and *Lemna* spp.), are also common in standing water between the islands, but together with the submerged vegetation (*Potomogeton* and *Ceratophyllum*, see Khedr, 1997) these communities are not as well discriminated within the FCC image. Collectively, however, the aquatic vegetation of the lake plays an important role in maintaining varied habitat for fish and bird species. Local modifications to emergent plant cover are particularly intense in the southern central sector of the lake and result from fish farming activities where selective reed cutting has created rectangular features at the scale of 100 m or less. Estimating the cover provided by aquatic plants is important because it promotes fish stocks (Kraïem et al., 2009) as well as restricting water movements (Thompson et al., 2009). The latter help in assimilating the excessive dissolved nutrients and in restricting the distribution of water pollutants (cf. Duning et al., 1996). For further discrimination, assessment and mapping of these aquatic plant communities in Lake Manzala, higher resolution

hyperspectral data could be applied (e.g. Underwood et al., 2006; Jollineau & Howarth, 2008).

Environmental change

The multi-temporal satellite images show considerable changes associated with the geomorphological development of all three lagoons, but changes in the total lake area and in the areas of open water and emergent vegetation have been greatest in Lake Manzala. The largest single recent change within Merja Zerga, the construction the Nador Canal in the 1950s (Ayache et al., 2009), predates the availability of satellite imagery. However, the suite of images available for this site from the 1970s onward demonstrate the lasting impact of this major hydrological engineering project in the form of the expanding delta where the canal discharges into the lagoon. Similarly, the growth of the delta associated with the more natural inflowing channel, the Drader River, is also demonstrated. The shape of the channel connecting the lagoon with the sea is also shown to have changed over the same period. The most dramatic changes, however, have been within the near landscape and are associated with the intensification of agriculture and expansion of the field system around the lagoon. Over a similar period, Ghar El Melh has seen some extension of agriculture around its northern and western shores, but the most persistent change is associated with sediment dynamics and the easterly migration of the sand spit delimiting the lagoon from the sea. This movement has probably been exacerbated by the building of the new fishing port in the northeast and alterations to the marine inlet channel since the 1970s (see Ayache et al., 2009).

Due to its larger size, the changes within Lake Manzala were examined in more detail. Images of this lake from 1973 to 2003 (Fig. 7) show a marked contraction of the lake margins and major changes in the distribution of emergent aquatic vegetation. According to the morphometric measurements made from the classified images of the Lake Manzala (Fig. 9), the overall size of the lake decreased by c. 50% between 1973 and 2003. Major reclamation in the northwest, southeast and south central areas of the lake since the early 1970s is clearly evident. These changes principally result from: (1) annexation of the northwestern sub-basin that existed prior to the late

1980s as a result of building the Trans-Manzala highway over the sandy ridges that marked the inner northern margin of the lake until the mid-1980; (2) construction of the El Salam Canal to the south of the lake across once extensive marshlands, which has since allowed reclamation of former lake bed on the landward side of the canal since 1983 (El-Quosy, 2006); and (3) rapid extension of land development westwards from the southeastern border of the lake since 1973. In the first of these areas, engineered fish farms were established but the northern tip of the El Deeba area has been affected by coastal erosion at least since 1973. Eroded material is transported east by long-shore currents (e.g. Stanley, 1988, 1996) causing siltation problems that affect the marine inlet channels to the lake. In the south, more than 250 km^2 of land were reclaimed for agriculture east of Matariya when the El Salam Canal was constructed east from the Damietta Branch of the Nile. This development has allowed for improved agriculture and road access to the town, but removal of surface water from newly reclaimed land in the area remains a persistent problem. In the southwest, the El Bshteer area is one of the fastest developing areas around the lake and the images show that between 1987 and 2003 quantitative changes amounted to local loss of more than 100 km^2 of lake area. In contrast, in the early the wetlands in this region of the lake extended to within <500 m of the Suez Canal. The overall contraction of Lake Manzala has reduced its water storage capacity, and other post-1970s hydrological modifications have affected water distribution (see Ayache et al., 2009). The engineered marine inlet channels in the El Gamil area permit Lake Manzala water to flow seawards and this can be tracked by satellite imagery. When the El Gamil sluices are open, the lake water, rich in nutrients and phytoplankton, can be seen to escape into the coastal zone (cf. the February 2003, Fig. 8d).

As a consequence of the recent changes in the lake's morphology and hydrology, the distribution of aquatic emergent vegetation in and around Lake Manzala has changed significantly. At least two major factors appear to be involved. The first is the freshening of the lake since the early twentieth century (see Flower, 2001) due to the inflow of large volumes of water from the drains in the south (Ayache et al., 2009; Thompson et al., 2009). This has permitted emergent vegetation to extend into the

central parts of the lake. At the same time the major reclamation activities have removed vegetation zones by encroachment into the former lake bed. While fish production has not changed markedly in the late twentieth century (Kraiem et al., 2009), the species composition has shifted in response to water quality and to changes in fisheries practices. Development of tilapia fisheries, particularly during the last 30 years, has been accompanied by increasing modification of the emergent vegetation. These modifications are mostly marked by the development of engineered fish farming in the annexed northwestern part of the lake and also by the linear vegetation features in the central southern part of the lake (especially around the lake port of Matariya). The expansion of these activities is evident within the remotely sensed images of the lake.

Although the extensive area of emergent vegetation in central Lake Manzala has expanded since the 1970s, much of this habitat has been lost from the marginal zones. As a result, the proportion of the lake covered in wetland vegetation has changed relatively little. The post-1970s spread of *Phragmites* reed swamp in the central area is a significant change that has doubtless affected water circulation patterns and water quality. Interestingly, this increase parallels changes recorded in the Lauentian Great Lakes where the dominance of several opportunistic plant species, including the common reed (*Phragmites australis*), has increased in recent decades (e.g. Wilcox et al., 2003). Temperature and water level regime have been implicated in the spread of common reed in North America, but in Lake Manzala reduced salinity seems the most plausible causative agent. In contrast to the Great Lakes, no specific management of the common reed has been undertaken in Lake Manzala, yet a combined field and remote sensing-based approach to develop a semi-automated detection and mapping technique to support monitoring and assessment of emergent plants (mainly *Phragmites* and *Typha*) offers an attractive way to tackle management of these reed beds.

Implications

Results of this study show that remote sensing when integrated with field survey and knowledge of site characteristics can offer a convenient approach for assessing North African coastal lagoons and

monitoring environmental change. Detecting geo-morphological and hydrological changes at the drainage basin scale has important implications for site management and near landscape development. The loss of lagoon habitat area is most alarming for Lake Manzala and together with major changes in the distribution of emergent aquatic plants and water circulation this must exert a major stress on the lake ecosystem. The fishery status is questioned at all three sites and likely further increases in eutrophication, siltation and reclamation will diminish lagoon habitats further. Predicted sea level rise may intervene but the ecosystems will surely change further so that monitoring into the future is essential.

Water quality and vegetation, which includes phytoplankton, macro-algae and submerged and emergent plants, are crucial aspects of aquatic biodiversity. The value of remote sensing to biodiversity and nature conservation is potentially demonstrated by tracking the nature and pace of the spatial changes in the lagoon habitat structure and quality. Further development of the work undertaken in this article should permit discrimination of the spectral signatures of both floating and shallow water submerged plants (Potamogeton and Ceratophyllum in Lake Manzala and Ruppia and macro-algae in Merja Zerga and Ghar El Melh) and divide the emergent plant communities according to the dominant species (Typha or Phragmites). Further development of remote sensing techniques for vegetation in Lake Manzala and the other Nile Delta lakes will offer an effective tool for monitoring opportunistic plant species such as water hyacinth. Elsewhere in Africa, remote sensing has successfully charted the large scale development of water hyacinth communities in Lake Victoria (Albright et al., 2004). Recent advances in remote sensing that include hyperspectral techniques (cf. Simis et al., 2005) offer more ways of improving the classification of both lagoon vegetation and water quality. Nevertheless, these remote sensing techniques cannot remove the need for species level and water quality ground survey information.

It is thought highly probable that, as the twenty-first century progresses, the effects of both direct human interventions and global climate change, including sea level rise, will increasingly threaten and disturb coastal lagoons. The Mediterranean has been identified as an area which is likely to experience acute water stress (Shindell, 2007) with important implications for aquatic ecosystems including those in the densely populated coastal zone. All three sites investigated in the MELMARINA Project (Flower & Thompson, 2009) urgently require continuity of the integrated monitoring and modelling programme as initiated by this project. Remote sensing is undoubtedly of major importance in this respect and, combined with new developments in this rapidly advancing field, will provide information needed by environmental planning and management authorities as well as environmental law enforcement agencies to help ensure the sustainability of these systems.

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