Integrated remote sensing and GIS techniques for biogeochemical characterization of the Tinto-Odiel estuary system, SW Spain

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Abstract The Tinto-Odiel estuary area in SW Spain presents a high concentration of industrial, agricultural and mining activities that seriously affect water quality, producing significant concentrations in trace metals and other contaminant elements. Previous studies have highlighted the important environmental effect of these contaminated waters discharged into the Gulf of Cadiz, contributing in a marked way to trace-metal concentrations in the Mediterranean Sea by water inflow through the Strait of Gibraltar. A global biogeochemical characterization of these waters was the main objective of a multidisciplinary research study funded by the European Union, in which remote sensing and GIS techniques, among other methodologies, were jointly applied. The main results confirmed the usefulness of this integrated methodological approach as an effective tool for the assessment of current biogeochemical conditions. Digital image processing provided valuable thematic information for temporal hydrodynamic analysis and water quality parameters mapping, which was integrated into a GIS database together with experimental information sampled in oceanographic cruises.

Keywords Water quality · Remote sensing · GIS · Tinto-Odiel estuary · SW Spain

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Introduction

One of the most famous sulphur mineralisations in the world, the "Iberian pyrite belt", is located in the upper part of the Tinto-Odiel River estuary system (Fig. 1). There exists archaeometallurgic evidence of mining activities in this region from Phoenician and Roman times, and later, in an intensive way, from the Industrial Revolution to the present day (Van Geen and others 1997; Ruiz and others 1998; Davis and others 2000; Leblanc and others 2000). These outcropping mineral deposits are affected by weathering processes, producing a gossan enriched in Cu, Pb, Zn, Cd, Au, Ag and other metals and incorporating mainly sulphate and heavy metals into surface streams and surface sediments (Borrego and others 2002). As a result of this polymetallic sulphur lixiviation, a characteristic "natural contamination" of the surface streams is observed, metal-rich (Nelson and Lamothe 1993) and with a strongly acidic pH, about two in the Rio Tinto "Red River" (Van Geen and others 1997; Elbaz-Poulichet and others 1999).

Furthermore, the area nearest to the estuary contains a high concentration of industrial sites dedicated to the production of chemicals, petrochemicals, fertilizers and paper, spilling their effluents (phosphate, fluoride, etc) into estuary waters (Ruiz and others 1998; Grande and others 2000). Intensive agricultural development with high use of nitrate fertilizers also contributes to the water contamination levels. As has been outlined by Van Geen

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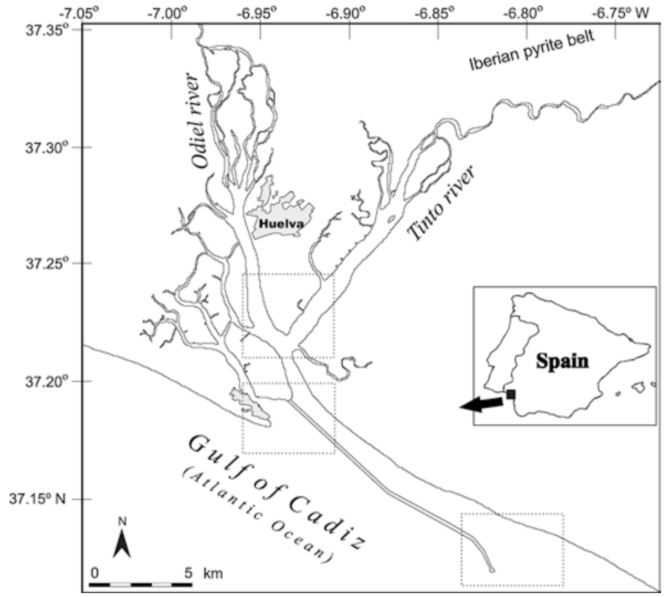

Fig. 1
Location map of the Tinto-Odiel estuary system, South West Spain. *Dashed rectangles* correspond to remotely sensed images shown in Fig. 3

and others (1991), Leblanc and others (1995) and Elbaz-Poulichet and others (2001b) this estuary system constitutes an important riverine source of trace-metal enrichment of Spanish shelf waters (Gulf of Cadiz) and consequently of the Mediterranean Sea by inflow through the Strait of Gibraltar.

The present study was developed in this environmental context regarding coastal water quality, in the framework of the TOROS Project funded by the Climate & Environmental Programme of the European Community. Its aim was to carry out multidisciplinary research into the biogeochemical processes controlling trace metal and nutrient concentrations in the Tinto-Odiel estuarine ecosystem, and their consequences for Atlantic shelf waters. A diverse group of specialists in environmental sciences, geology, oceanography, hydrogeology, biogeochemistry, marine geology and remote sensing, belonging to several European universities, were involved. In this paper, we show a synthesis of the contribution of remote sensing and GIS (Geographical Information Systems) techniques to managing the spatial information used in this environmental study (see Elbaz-Poulichet and others 2001a for a biogeochemical synthesis). The objective pursued with this application was producing a set of thematic maps from remote sensing imagery to complement experimental information, in order to interpret the spatial distribution of relevant water quality characteristics, such as turbidity, water temperature, chlorophyll, etc. Images were also used for a multitemporal study of littoral dynamics using turbidity and to elaborate spatial models for biogeochemical characteristics, e.g., suspended sediment or chlorophyll-a, based on multiple regression and geostatistical methods. Finally, thematic maps resulting of these applications were integrated into a GIS database as vector or raster layers, together with abundant information gathered in water surveys and oceanographic cruises, with the goal of achieving more efficient planning in water quality management.

The Tinto-Odiel estuary system

The Tinto-Odiel estuary is located on the Atlantic southern coast of the Iberian Peninsula in Huelva province, SW Spain (Fig. 1), along a mixed-energy mesotidal coast, with mean tidal range of 2.10 m and slight diurnal inequality (Borrego and Pendon 1989). These rivers are 83 and 128 km long, respectively, and the average annual discharge is estimated at around 100 hm^3/yr. The common drainage basin covers an area of some 4,000 km^2 and the two rivers meet in a single channel known as "Padre Santo", 20 km long and 3 km wide, where there occur exchange processes between estuarine and coastal waters. As mentioned above, the most remarkable environmental aspect of this estuary system is related to the physical-chemical characteristics of the water; it is rich in trace metals and has a strongly acidic pH value (pH 2 in the Tinto River), contrasting with that measured in salt waters of the lower part of the estuary (pH 7). Two significant factors in the hydrodynamic behaviour of the estuary system, namely the fluvial contribution of water and sediments and the tidal cycle, have a direct effect on water mixing conditions, sedimentation rate and sediment deposits in the fluvial-marine system. These aspects are fundamental for a correct comprehension of the functioning of this ecosystem and its relation with the biogeochemical characteristics of the estuarine waters (Ojeda and others 1995b).

Remote sensing images and water quality data

Digital satellite and airborne sensor images along with a large amount of experimental data, mainly concerning biogeochemical water analysis, were made available for this study. A set of 12 Landsat Thematic Mapper (TM) images representative of diverse hydroclimatic and hydrodynamic situations of the study area, were supplied by the Environmental Agency (Agencia de Medio Ambiente, AMA) of the Regional Government of Andalusia (Junta de Andalucia) (scene 202–34 and period 1985–1997). Furthermore, Airborne Thematic Mapper (ATM) images obtained at different dates were acquired by INTA (National Institute for Aerospatial Techniques), using a Daedalus sensor DS-1268 with CZCS configurations (Fig. 2a). These airborne multispectral images are composed of 11 bands in the range 0.4–13 mm and a spatial resolution of 7 m (Jensen 2000). All images were corrected for atmospheric and geometric distortions using standard procedures (see Lillesand and Kiefer 1999) and eventually georeferenced along with all additional experimental data to the UTM coordinate system.

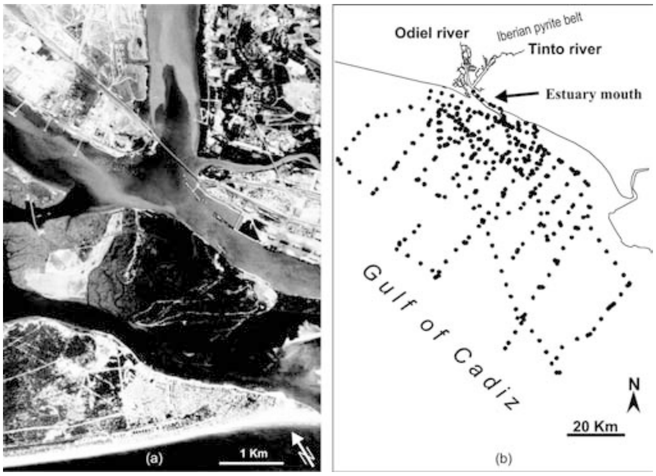

Fig. 2
a) Daedalus ATM colour composite image (RGB 542) of the confluence of the Tinto and Odiel Rivers. **b**) Oceanographic sampling campaign carried out in 1997. Sampling points are shown as *dots*

The experimental data collection campaign was designed to take place at the time of the satellite and aircraft overpass. Experimental data included a set of sampling points in which the following water quality characteristics were analysed: conductivity, temperature, suspended sediments, pH, turbidity, organic matter, chlorophyll (a, b and c), Secchi depth and heavy metals Cu, Fe, Ni, Zn, Mn, As, Hg, Fe, Zn, Cd (AMA 1995). Information on tidal conditions, i.e. height, tidal coefficient and the phase, was obtained from the tidal annuary for the Huelva harbour.
During the development of the TOROS Project more detailed information concerning biogeochemical parameters was also gathered. Data were obtained at different dates for the three main parts of the estuary system, namely the fresh, mixing and marine water zones. For this purpose four oceanographic cruises were carried out in November 1996, June 1997, April 1998 and October 1998, in which water samples at different depths with a Niskin bottle and a 24 bottle General Oceanics rosette were taken (Fig. 2b). In every sampling campaign around a hundred samples, uniformly distributed in the estuary and the adjacent marine shelf, were analysed for major elements, trace metals, nutrients, phytoplankton and chlorophyll. The main physical-chemical water characteristics, i.e. temperature, pH, conductivity and dissolved oxygen were also measured (Elbaz-Poulichet and others 1998).

Remote sensing techniques applied to water quality characterization

Remote sensing techniques are increasingly applied to coastal zone studies to analyse various aspects of water quality, such as chlorophyll concentration, water turbidity, concentration of suspended sediments and water temperature (e.g., Rimmer and others 1987; Forster and others 1993; Pattiaratchi and others 1994; Fraser 1998; Parada and Canton 1998; Kondratyev and others 1998; Tassan 1998; Allee and Johnson 1999). For this specific area diverse activities focusing on these aspects have been carried out in the context of research programmes to monitor the quality and dynamics of marine waters using remote sensing techniques, e.g., Fernandez-Palacios and others (1995, 1997), Ojeda and others (1995a, 1995b). A general methodology for TM and ATM image treatment was established from these previous studies, focusing on two fundamental objectives: firstly, a space-time analysis of the main characteristics of the hydrodynamic processes observed in the functioning of the river-estuary-ocean system, using turbidity as a “natural tracer”. Secondly, the elaboration of numerical models for spatial characterization of water quality parameters, e.g., suspended sediments or chlorophyll-a, by integration of multispectral images and experimental water quality data. Two different numerical approaches, based on classical multiparametric regression and geostatistics respectively, were used and compared in order to elaborate biophysical parameter models.

River-estuary-ocean system dynamics

Remote sensing shows great interest for the study of estuarine zone dynamics due to spatial-time completeness and homogeneity of image data. Water turbidity is widely accepted as a representative parameter for the littoral dynamic study that can be analysed from remotely sensed data. This parameter has been examined in detail by diverse authors from digital images at different spatial (scale) and spectral resolutions, e.g., ATM (Pattiaratchi and others 1986), SPOT HVR (Lathrop and Lillesand 1989), Landsat TM (Pattiaratchi and others 1994), Advanced Very High Resolution Radiometer (AVHRR) (Stumpf and others 1999), Compact Airborne Spectrographic Imager (CASI) (Uncles and others 2001). In the present study, the Landsat TM image set representing different hydrodynamic situations of the estuary was analysed to interpret the degree of water turbidity with respect to the tidal cycle (height, phase and tide coefficient). Previous work on the study area carried out by Ojeda (1995a, 1995b) suggested that the TM2 band could be used to elaborate turbidity maps for a spatio-temporal analysis of the horizontal movement of surface water. Following this criterion, the TM2 band for each image was segmented by density slicing considering four turbidity classes. The images obtained were clustered into two groups according to low and high tide conditions, in order to analyse the temporal homogeneity of the turbidity. Grouping of the set of TM2 segmented images was carried out using the Principal Component (PC) multivariate statistical method. PC1 representing an average temporal situation (maximum variance) was selected for the analyses.

Airborne image analysis

Airborne image treatment carried out by INTA was mainly aimed at obtaining thematic maps of the spatial distribution of suspended sediments (channel ratio 6/3), chlorophyll (channel ratio 4/2) and water temperature (channel 12). Combinations of band ratios of the visible channel helped to remove the sunglint effect. Diverse water colour maps from RGB colour composites were elaborated to facilitate a qualitative interpretation of the waters in the estuary, based on visible channels 1–6 and other infrared channels of interest for this study. The thermal infrared channel (8.5–13 μm) was found to be very useful to analyse structures created by tidal movement. Apparent surface brightness temperature (T) was retrieved from image digital number (DN) using the following expression: T(°C)=(0.9DN+10.5)/5. This transformation was derived from in-flight calibration black bodies with accuracy 1DN=0.18 °C. Figure. 3 shows images of chlorophyll and water surface temperature at three locations: the confluence of the Tinto and Odiel Rivers, the Padre Santo channel, and the estuary mouth.

Integration of digital images and experimental data for spatial co-estimation of water quality parameters

In addition to photointerpretation tasks as those shown above, remotely sensed data can also be integrated with experimental data in order to construct spatial distribution models of biogeochemical characteristics. This approach requires the assumption that both variables, radiometric and experimental data, are spatially correlated. Such a hypothesis is largely acceptable in many practical cases, such as the one presented here, where some of the water quality characteristics, e.g., suspended sediments or chlorophyll, have a direct influence on the spectral response of the water. Two numerical models, multiple regression and co-kriging (Journel and Huijbregts 1978), based on different conceptual approaches were tested.

Multiple regression methodology has been used in diverse situations to integrate digital image information and experimental data (e.g., Aranuvachapun and Walling 1988; Forster and others 1993; Reddy 1993). The regression model of the water quality parameter studied (the dependent variable) is obtained from a set of radiometric bands (independent variables) statistically correlated with the former, expressed as a linear combination of radiometric data by means of regression coefficients. The resulting equation allows us to estimate a water quality parameter at any image pixel x using a polynomial function written in terms of digital numbers of the n bands. One criticism of the above method is that it does not consider the spatial variability structure of the variables, an aspect that is considered of special interest in increasing the accuracy of the results obtained. The co-kriging method is a multivariate geostatistical technique that offers an excellent approach to increase the estimation accuracy of the main variable, i.e. suspended sediment concentration, by considering spatial cross correlation with secondary variables, i.e. TM radiometric bands. The technique requires us to define a spatial coregionalization model for all variables, experimental and radiometric data, based on the variogram function analysis (Chica-Olmo and Abarca 1998). The estimator of a water quality parameter, Z_1^*, at any point or pixel u in the estuary is given by resolving the co-kriging system (Journel and Huijbregts 1978; Goovaerts 1997):

$$Z_1^*(u) - m_1(u) = \sum_{\alpha_1=1}^{n_1(u)} \lambda_{\alpha_1}(u)[Z_1(u_{\alpha_1}) - m_1(u_{\alpha_1})] + \sum_{i=2}^{N_v} \sum_{\alpha_1=1}^{n_i(u)} \lambda_{\alpha_1}(u)[Z_i(u_{\alpha_i}) - m_i(u_{\alpha_i})]$$

where $\lambda_{\alpha_1}(u)$ is the weight assigned to the primary datum $z_1(u_{\alpha_1})$ and $\lambda_{\alpha_i}(u), i>1$, is the weight assigned to the secondary datum $z_i(u_{\alpha_i})$, and $m_1(u)$and $m_i(u_{\alpha_i})$ denote expected values of the primary data $\{z_1(u_{\alpha_1}), \alpha_1 = 1, ..., n_1\}$ and the (N_v-1)secondary attributes $z_i, \{z_i(u_{\alpha_i}), \alpha_i = 1, ..., n_i, i = 2, ..., N_v\}$, respectively.

Different tests were made choosing groups of the best correlated bands with the characteristic to be estimated (e.g., TM2 and TM3 for suspended sediment). Co-kriging estimation error maps were also derived to assess the reliability of the estimated values. In addition, results

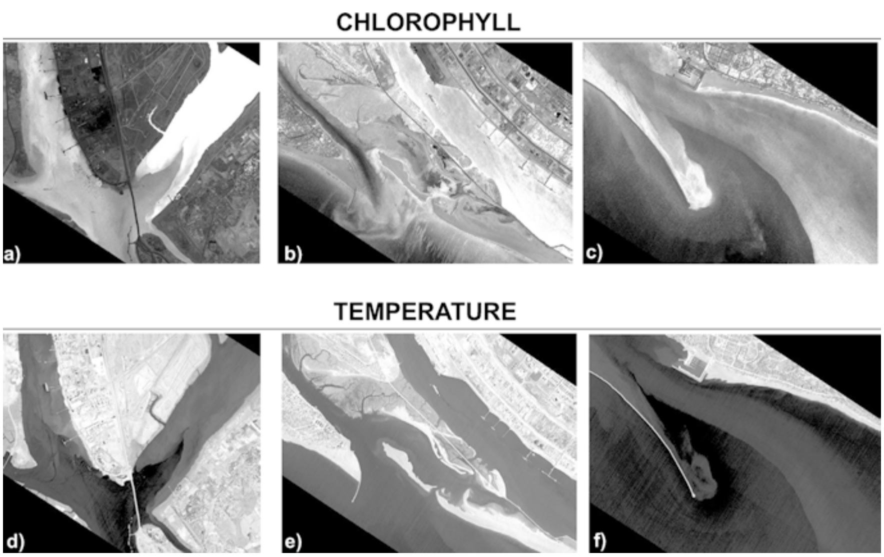

Fig. 3
Chlorophyll (*upper row*) and temperature (*lower row*) images derived from ATM data for three estuary areas: **a**) confluence Confluence of the Tinto and Odiel Rivers, **b**) Padre Santo channel, and **Cc**) estuary mouth. Image locations are shown as *dashed rectangles* in Fig. 1

obtained by co-kriging were compared with those obtained by regression.

GIS implementation

GIS technology is becoming a powerful tool in the integration and spatial analysis of riverine, estuarine and coastal environmental information (Mattikalli and others 1996; Lathrop and others 2001). Many of the biogeochemical characteristics studied in the Tinto-Odiel estuary are physically and statistically interrelated and in many cases show spatial dependence. This fact along with the inherent spatial distribution of experimental data makes GIS a suitable tool for such analysis, especially for information management and helping in the decision making process (Burrough and McDonnell 1998). Thus, results from remote sensing image processing were straightforwardly integrated into the GIS database, supplying basic information for better environmental management and regional planning of the area investigated.
Figure 4 shows a general scheme of the methodology applied for GIS implementation, in which two main parts are highlighted, (a) the creation of a relational database and (b) the user's interface for spatial analysis in order to establish a decision support system. Input from analogue maps was carried out by manual digitizing using a tablet, a flat scanner or keyboard input to create vector layers. Remote sensing applications provided important thematic maps relating to littoral dynamics and water quality characterization in raster format. Furthermore, careful attention was paid to spatial analysis of the biogeochemical data, which were geostatistically analyzed to generate raster layers of the principal variables by kriging estimation. In this way, a complete georelational database was elaborated to be used as a tool for thematic map creation and interactive spatial database querying (Table 1). For this purpose, a comprehensive support system for remote querying and retrieving of data tables and thematic maps via the Internet was developed. The support system was implemented using the C programming language, Unix shell and Perl scripts.

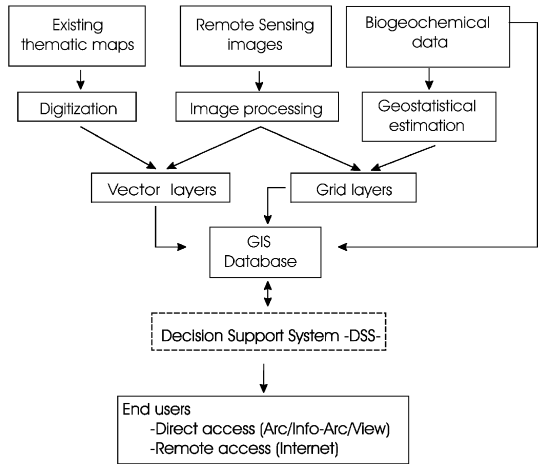

Fig. 4
Flow chart showing the main part of the GIS implementation methodology

Results

Remote sensing techniques allowed us to generate a set of images and thematic maps of turbidity at different dates showing valuable information on river-estuary-ocean system dynamics. Turbidity images generated using PCA and TM data showed, as expected, high values where turbidity was high. This allowed the interpretation of the main features of the dynamic functioning of the estuary for the two tidal situations. Figure. 5 shows the spatial distribution of the PC1 values for three situations ranging from high to low water condition in the estuary area. At high tide, the Tinto River shows high turbidity in the headwaters and the intermediate part; a moderate degree of turbidity is observed both in the Odiel River and in the confluence zone of the two rivers, while turbidity is low in the main "Padre Santo" channel. At low tide, the outer

Table 1
Summary of the spatial data layers used to populate the Tinto-Odiel estuary GIS database

	Cover	Type	Acquisition	Scale/resolution
Remotely sensed data	Chlorophyll-a Turbidity SSC Heavy metals	Raster	Magnetic tape	30x30 m
Ancillary data	Topography Geology Mines Industry Hydrology Urban Roads	Line	Digitizing	1:50,000
Biogeochemical data	Chemical: nitrates, nitrites, silicates, phosphates, trace elements, pH, etc. Biology: phytoplankton, chlorophyll, etc.	Point	Database	–

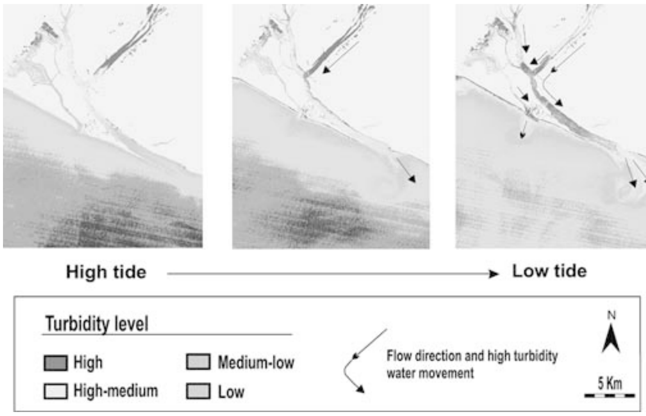

Fig. 5
PC1 images created from Landsat TM images showing turbidity levels in the Tinto-Odiel estuary for high to low tide situations

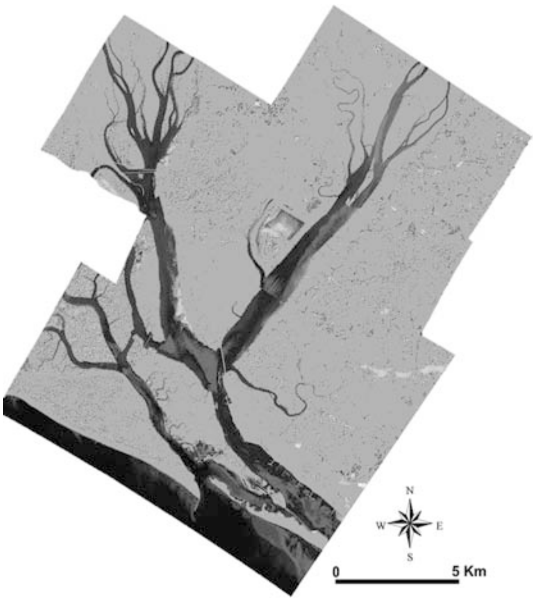

Fig. 6
Water surface temperature of the estuary zone for April 23th23rd, 1998 (12.00 GMT), derived from the ATM thermal infrared channel (8.5–13 mm). The image was composed merging the different flight lines: the uncertainity in the georeferencing of each image is causing the displacements in the flight lines junctions. Temperature increases from grey tones (*colder water*) through deep blue to light blue and green (*hotter points*). Temperature resolution is 0.18 °C

waters of the estuary show low-medium values of turbidity, conforming a parallel band to the coast formed by mixing water drained by the estuary and littoral water. Medium-high values of turbidity are found at the end of the principal channel and in the upper and middle sections of the Odiel and Tinto Rivers, with patterns of turbidity plumes being generated in the main and secondary channels.
In addition, a set of thematic maps of suspended sediment, chlorophyll and surface water temperature were obtained from airborne images. Structures created by tidal movement were outlined using the ATM thermal infrared channel. Figure. 6, which corresponds to a colour-coded 8-bit mosaic of the water surface temperature derived from ATM images, clearly shows tidal structures (grey tones) at the confluence of the Tinto and Odiel Rivers, at their tributaries, at the Padre Santo channel, and at the outer waters of the estuary.
Excellent results were obtained from the integration of digital images and experimental data. Several parameters were estimated and mapped using regression. For instance, suspended sediment concentration (SSC) was estimated using the following equation for the best correlated bands (TM1, TM2, and TM3) for the Landsat TM image dated 25 November 1994:
$SSC(x)=48.43+0.94 TM2(x)-0.92 TM1(x)+0.89 TM3(x)$.
Equivalent formulas were deduced for other dates. Experiments performed using geostatistical co-estimation gave, however, the best results in terms of estimation accuracy. Variographic analysis showed that all variables were to some extent spatially autocorrelated and most of them were spatially interrelated (Fig. 7a). Relevant parameters were estimated and mapped using kriging and-cokriging (Fig. 7b). For instance, TM2 and TM3 bands were used as secondary variables in spatial co-estimation of suspended sediment concentration (Fig. 7c). A detailed analysis of the results obtained by both methods concluded that co-kriging was the more accurate technique. Figure. 7d represents a transect along the estuary area showing a comparison of the profiles of suspended sediment concentration estimated by multiple linear regression and co-kriging, where the latter fit better experimental observations. Co-kriging method not only gives an optimal estimation but also allows us to evaluate the estimation error, a parameter that describes in terms of probability the reliability of the estimated value (error maps).
Finally, a GIS spatial database comprising existing thematic maps, thematic information resulting from image treatment and experimental information relating to water quality characteristics (oceanographic cruises and sampling campaigns), was available for project researchers and decision makers. Project users could send interactive spatial queries to the georelational database using a standard web browser to generate reports on the biogeochemistry of the Tinto-Odiel estuary. The spatial database query system included a front-end consisting of a graphical user interface implemented as several web pages, including one for multi-class map overlay analysis (Bonham-Carter 1994). Figure. 8 shows an example of the user interface as presented to the end-users of the Tinto-Odiel estuary biogeochemical database.

Discussion and conclusions

Water pollution in the Tinto-Odiel estuary system represents a major environmental hazard that needs to be taken into consideration in the suitable development of the region. Contaminated metal-rich waters, characterized by a highly acidic pH are discharged into the Gulf of Cadiz representing an important inflow of trace-metal concen-

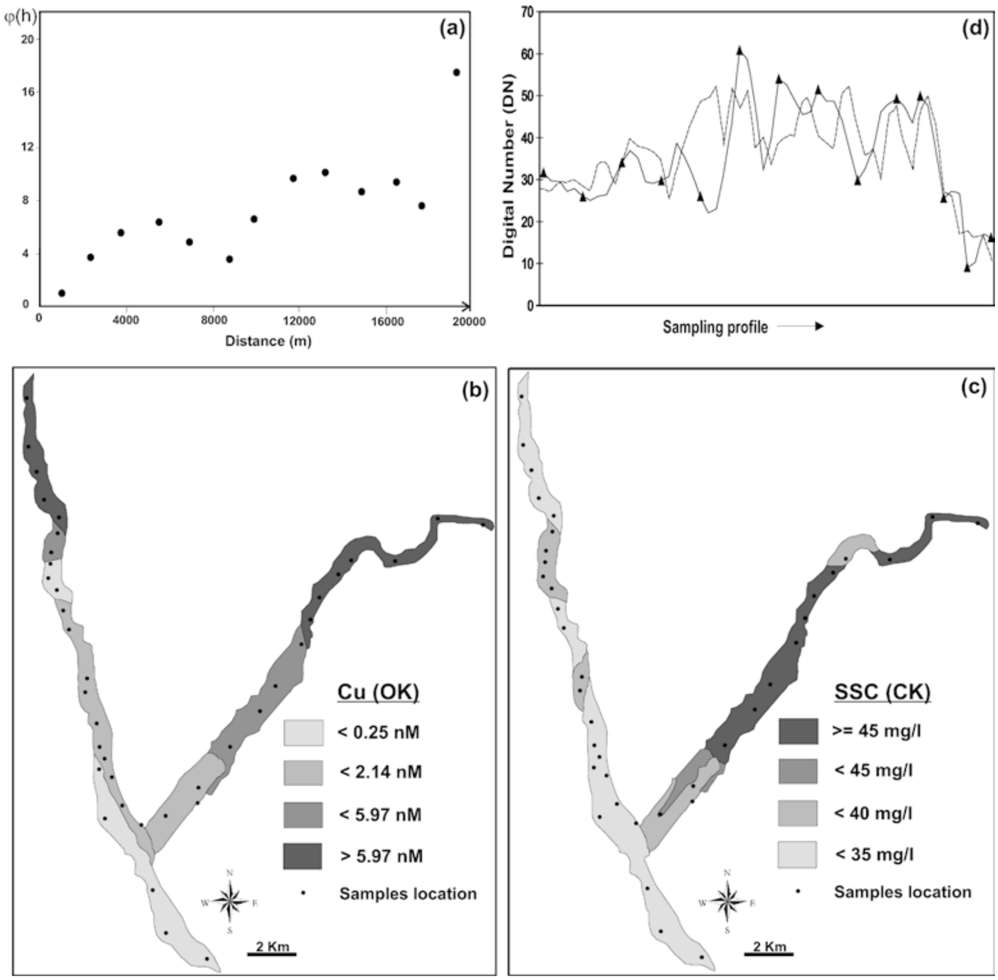

Fig. 7
Geostatistical analysis results. **a**) Experimental variogram for Cu. **b**) Map of Cu derived by ordinary kriging. **c**) Suspended sediment concentration map derived using co-kriging with TM2 and TM3 bands as secondary variables. **d**) Profiles of suspended sediment derived by co-kriging (*continuous line*) and multiple linear regression (*dashed line*). Field experimental observations are shown as *triangles*

tration into the Mediterranean Sea. In this study, we have described a multidisciplinary approach based on remote sensing and GIS integration for biogeochemical data management. The results obtained confirm the synergy of the combined use of the two techniques for better environmental management and more effective regional planning.

Some of the biogeochemical variables characterizing water quality have been examined from satellite and airborne sensor images. Digital image treatment enabled us to elaborate diverse thematic maps, showing the relevant role played by remote sensing imagery in the environmental characterization of this contaminated estuarine ecosystem. Thus, turbidity and other water quality characteristics were mapped and introduced into the GIS in conjunction with environmental and territorial data sets. Moreover, we showed the usefulness of radiometric information as a complementary information source in geostatistical models of spatial co-estimation of water quality characteristics. The GIS implementation steps consisted of the creation of a relational database including a comprehensive georeferenced data set for remote query via the Internet and the elaboration of specific modules for spatial analysis and management information. This latter step was developed by means of user interfaces and allowed us to build a decision support system for more efficient planning in

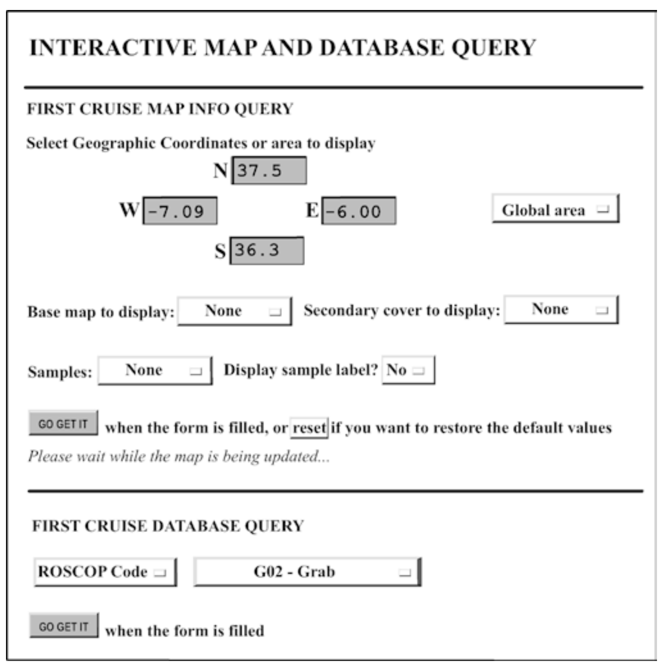

Fig. 8
Web page showing an example of the graphical user interface for remote and local access to the Tinto-Odiel estuary GIS database

water quality control and policy. An aspect of great interest for future work in relation to this study is the development of a GIS that accounts for time and the third spatial dimension of water quality data, customarily recorded in field surveys and oceanographic cruises, simultaneously.

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