INT. J. REMOTE SENSING, 1990, VOL. 11, NO. 2, 301–311

A multi-temporal study of chlorophyll-*a* concentration in the Albufera lagoon of Valencia, Spain, using Thematic Mapper data

M. J. LÓPEZ GARCÍA

Departament de Geografia, Facultat de Geografia i Història, Universitat de València, Ap. 22060, 46080 Valencia, Spain

and V. CASELLES

Departament de Termodinámica, Facultat de Física, Universitat de València, 46100 Burjassot, Spain

(Received 5 August 1988; in final form 21 March 1989)

Abstract. A multi-temporal study of chlorophyll-*a* concentration, has been made by means of Landsat-5 Thematic Mapper (TM) band 1 (0·45–0·52 μm) in the Albufera of Valencia, a hypertrophic lagoon of shallow depth. The relationship between this parameter and satellite data was set up from *in situ* measurements and concurrent satellite data obtained in a campaign from 22 July 1985. This relation has been applied to images of different dates by using a simple procedure of correction, which is based on the use of selected surfaces whose ground reflectance is assumed to be constant with time. Good results were obtained and chlorophyll-*a* concentrations have been determined with an error of 20 per cent.

1. Introduction

In order to carry out a multi-temporal study of water quality in lakes or natural reservoirs, it is necessary to solve two major problems: (1) the determination of an empirical relation between the trophic parameter studied and the radiance values recorded by the sensor and (2) the use of a standard procedure which permits the application of this relation to images of other dates. The first problem involves physical considerations of the interaction of radiation with particles dissolved in water and has been resolved successfully by different authors (Holyer 1978, Lillesand *et al.* 1983, Khorram 1985, Lathrop and Lillesand 1986). The second one, however, has not been completely solved, although various attempts have been made (Carpenter and Carpenter 1983, McFarlane and Robinson 1984, Verdin 1985).

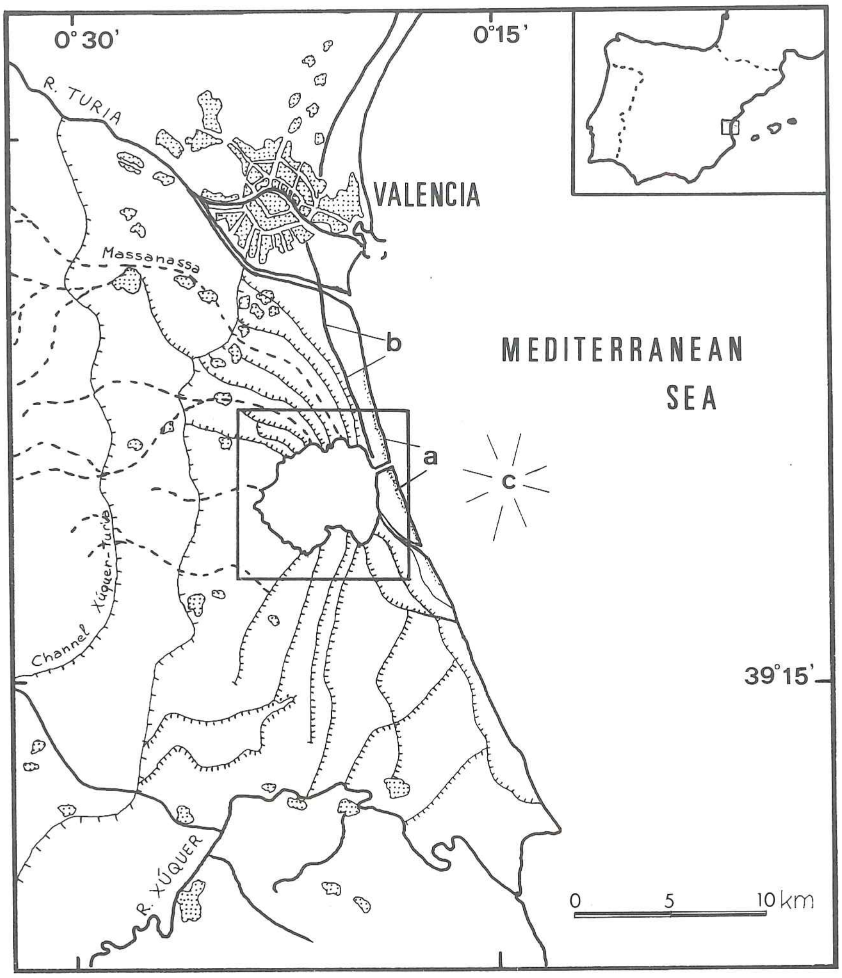
The solution to the second problem requires the evaluation of the changing effect of the atmosphere. This can be achieved by using an atmospheric radiative transfer model, such as one of those of Turner and Spencer (1972), Otterman and Robinove (1981), Kneizys *et al.* (1980), Tanré *et al.* (1986), etc. However, these models need input data on the amount, physical properties and size distribution of the atmospheric aerosol. Frequently, these magnitudes are not available in the area studied and, consequently, data from the nearest meteorological station (which can be 50 km away) have to be used.

In order to avoid this major difficulty, we have employed an alternative procedure which permits the correction of several images in a relative way, just taking one of them as reference. This method is based on the use of some points that can be easily identified in the image, whose ground reflectances do not vary substantially throughout the year.

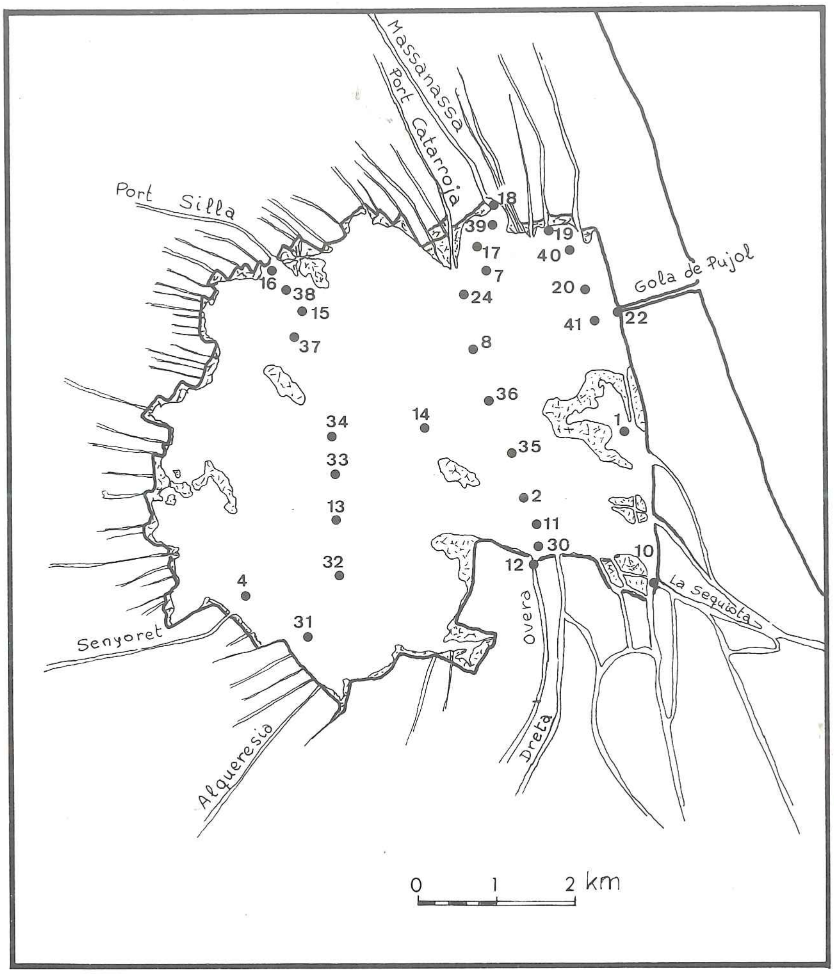
2. Study area

The Albufera of Valencia is a litoral lagoon, situated on the Mediterranean coast of Spain, 10 km south of the city of Valencia (figure 1 (*a*)). It is important both because of its size (the third largest in Spain) and the ecosystem (flora and fauna) that exists there. Almost circular in shape, 8 km in diameter and 0·75 m in depth, it occupies the central part of a wide wetland area (223 km^2) which lies between the Xúquer and Turia rivers and is mostly dedicated to rice crops. The Albufera is connected to the sea through two natural and one artificial channels called 'golas'. Water flow is regulated by means of floodgates in such a way that the lagoon's water level is maintained according to rice culture needs (Rosselló 1979).

The water reaching the lagoon comes from a great number of irrigation channels and ravines which carry waters of various origin and quality (Soria 1987), including (1) rain waters, (2) waters from the rivers Turia (to the north) and Xúquer (to the south and south-west) which reach the lagoon through the irrigation channels, (3) agricultural waters from the rice fields (coming mostly through the southern channels Overa and Dreta) and (4) industrial and urban residual waters (mostly from the north).



(*a*)



(*b*)

Figure 1. Map of the study area. (*a*) Showing the subscene corresponding to the Albufera and the surfaces of unchangeable reflectance used for the correction method (a = sand, b = asphalt and c = water). (*b*) The sampling sites visited in the campaigns.

From a biological point of view, the Albufera is a hypertrophic system, i.e., a very eutrophic area characterized by (1) shallow depth and limited water circulation, (2) unequilibrated nutrients and oxygen regime and (3) a very high productivity—the biomass can exceed 150 mg/l (600 mg/m^3 of chlorophyll-*a*). However, the Albufera differs from other hypertrophic areas because of the system of water renovation through the golas, since the escape of such waters is vital to the system (Soria 1987).

3. Empirical relation

3.1. *Water quality data*

Chlorophyll-*a* data used in this study were acquired in the frame of a European Space Agency (ESA) pilot project (Caselles *et al.* 1987), by the Departament de Ecologia, Facultat de Biologiques (Universitat de València) in the campaigns carried out on 22 July, 17 September and 20 November 1985, nearly coincident with the

Table 1. Thematic Mapper band 1 (TM 1) and chlorophyll-*a* (Chl.*a*) data of 22 July 1985 in the sampling sites.

Sampling sites	Time (GMT)	Chl.*a* (mg/m^3)	TM 1 (DN)
1	11·27	346	89
4	9·10	506	87
7	10·10	260	90
8	9·40	514	88
11	9·00	210	92
13	9·30	578	86
20	10·50	486	87
24	9·55	542	88
30	8·45	317	88
31	9·00	515	87
32	9·20	451	88
33	9·40	717	86
34	9·50	630	87
35	9·15	397	89
36	9·30	462	88
37	10·00	611	87
38	10·10	488	89
39	10·22	213	93
40	10·40	499	87
41	11·05	475	87

Table 2. Chlorophyll-*a* measured values on 17 September and predicted values obtained by means of equation (10) from TM 1 digital numbers. The last column shows the differences between measured and predicted chlorophyll values.

Sampling site	Time (GMT)	Chl.*a* (mg/m^3): measured	TM 1 (DN)	Chl.*a* (mg/m^3): predicted	Differences (mg/m^3)
1	14.00	494	68	455	39
8	9.55	375	69	391	−16
10	16.15	354	72	248	106
11	8.15	193	77	116	77
12	11.00	9	79	86	−77
13	15.50	625	68	455	170
14	7.45	457	70	336	121
15	17.10	538	69	391	147
16	18.40	224	70	336	−112
17	17.50	509	70	336	173
18	20.30	129	73	213	−84
19	12.45	99	74	183	−84
20	10.15	498	70	336	162
30	11.25	20	76	135	−115
33	16.15	482	69	391	91
34	16.25	420	70	336	84
35	9.40	507	69	391	116
36	9.47	497	69	391	106
41	10.00	370	70	336	34

Table 3. Chlorphyll-*a* measured values on 20 November, and predicted values obtained by means of equation (11) from TM 1 digital numbers. The last column shows the differences between measured and predicted chlorophyll values.

Sampling site	Time (GMT)	Chl.*a* (mg/m^3): measured	TM 1 (DN)	*Chl.a* (mg/m^3): predicted	Differences (mg/m^3)
1	9·00	451	55	375	76
2	9.35	472	55	375	97
8	9.55	452	54	524	−72
11	9.27	99	56	269	−170
22	10.10	457	55	375	82
30	9.20	40	57	193	−153
35	9.42	398	55	375	23
36	9.50	532	54	524	8
41	10.05	458	54	524	−66

Landsat overpass (tables 1, 2 and 3). Samples were taken at surface level (0·2 m) by two boats (figure 1 (*b*)), going over all of the lagoon surface. July data were employed in the determination of the relation between *in situ* and satellite data, whereas September and November data were employed to check the results obtained by means of the correction procedure used in the multi-temporal analysis.

Quantitative determination of chlorophyll-*a* concentrations, chl.*a* (mg/m^3), were made in the laboratory by spectrophotometric analysis, solving chlorophyll extracts in a 1:1 solution of acetone 90 per cent and dimethyl-sulphoxide according to the classical method described by Strickland and Parsons (1968)

$$\text{chl.}a = (11{\cdot}6\ A_{666} - 1{\cdot}31\ A_{645} - 0{\cdot}14\ A_{630})\ (v/Vz) \qquad (1)$$

where: A_{665}, A_{645} and A_{630} are the solution absorptions at wavebands of 665, 645 and 630 nm, v is the extract volume (ml), V is the volume of the filtered sample (l), and z is the optical path length of the spectrophotometric tray (cm).

3.2. *Satellite data*

This project has been carried out using Landsat-5 Thematic Mapper images corresponding to 16 March, 22 July, 17 September and 20 November 1985. Sub-scenes of 256 × 256 pixels covering the study area were processed, corrected for striping and smoothed. The sampling stations were located on the digital images with the aid of people in charge of taking samples at the *in situ* campaigns. The mean error in the location of the sites was estimated to be 100 m for the samples taken in the lagoon and so averaged values from a size-window of 4 × 4 pixels were recorded. However, on the sites placed near the borders or at channel mouths, where location is easier, the pixel value was taken. Likewise, every one of these areas was critically examined in order to reject the points placed in very heterogeneous areas since they could induce errors in the regression analysis, because the mean value obtained from the satellite and the sampling measurement can be very different in these ones.

3.3 *Regression analysis*

The data from the campaign of 22 July 1985 were employed to obtain the best relation between chlorophyll-*a* concentrations (mg/m^3) and the digital values obtained in every spectral band, DN_i (0–255) where $i=1, 2, \ldots, 7$. In order to determine a simple predictive equation that could be easily applied to multiple images, linear regression techniques were used instead of multiple regression analysis. This relation was (López-García and Caselles 1987)

$$\ln \mathrm{chl}.a = -0{\cdot}172\,\mathrm{DN}_i + 21{\cdot}2 \tag{2}$$

with a correlation coefficient, $r=-0{\cdot}93$, and a standard error of estimate $\varepsilon=0{\cdot}13$, which is equivalent to a mean error of 10 per cent in chlorophyll-a determination (figure 2).

4. Atmospheric correction

Equation (2) is only valid for the image of 22 July 1985, and the application of this relation to images of different dates requires the evaluation of the atmospheric effect over every image. This is usually done by means of an atmospheric radiative transfer simplifed model (Rollin *et al.* 1985). Thus, for a given spectral band, and assuming homogeneous Lambertian surfaces (Deschamps *et al.* 1982), the atmospheric effect can be expressed as

$$\rho^* = t_g\left[\rho_a + \frac{T(\theta_S)\rho}{1-\rho s}T(\theta_v)\right] \tag{3}$$

ρ^* being the apparent reflectance of the Earth–atmosphere system, given by

$$\rho^* = \frac{k\pi L}{E\cos\theta_S} \tag{4}$$

where k is the correcting factor for the changing Earth–Sun distance, L is the spectral radiance which reaches the satellite, E is the solar irradiance at the top of the atmosphere, θ_S is the solar zenith angle, t_g is the gaseous transmittance, ρ_a is the intrinsic atmospheric component, $T(\theta_S)$ is the total transmittance for incident solar radiation (direct and diffuse), ρ is the ground surface reflectance, $T(\theta_v)$ is the total transmittance for reflected solar radiation, θ_v is the satellite view angle and s is the spherical albedo.

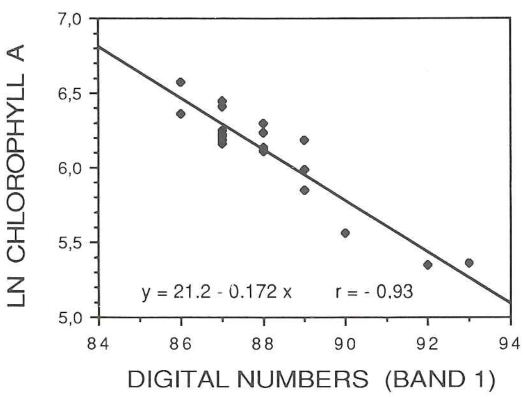


Figure 2. Fitting corresponding to 22 July 1985 data.

Since $t_g \simeq 1$ and ρs is a very small quantity (Deschamps *et al.* 1983), equation (3) can be written as

$$\rho^* = a + b\rho \tag{5}$$

where $a = t_g \rho_a$ and $b = T(\theta_S)T(\theta_v) = T(\theta_S, \theta_v)$.

Equation (5) permits one to estimate the relative atmospheric effect between two different images. In fact, if we suppose that ρ remains constant with time and we apply equation (5) to two different dates, we will obtain

$$\rho_1^* = a'\rho_2^* + b' \tag{6}$$

where ρ_1^* and ρ_2^* are the apparent reflectances obtained on two different dates for the same surface, $a' = T_1/T_2$ and $b' = t_{g1}\rho_{a_1} - t_{g2}\rho_{a2}(T_1/T_2)$.

Then, if we take into account expression (4) as well as the fact that the calibration function for the Thematic Mapper bands are linear

$$L = a_0 + a_1 \, \mathrm{DN} \tag{7}$$

then, equation (6) can be expressed as a function of the digital numbers, DN, as

$$\mathrm{DN}_2 = a''\mathrm{DN}_1 + b'' \tag{8}$$

where

$$a'' = \frac{\cos\theta_{S1}}{\cos\theta_{S2}} a'$$

and

$$b'' = \frac{1}{a'} \frac{\cos\theta_{S1}}{\cos\theta_{S2}} (a'a_0 + b') - a_0$$

In this way, a multi-temporal study can be carried out without the need to convert digital numbers into reflectance values, which obviously reduces the computing time.

5. Multi-temporal analysis

To apply this method, three surfaces of constant ground reflectance were selected: (1) dry sand of the littoral barrier which close the lagoon, (2) the asphalt of a highway which lies next to the study area, and (3) sea water at 6 km from the coast. The location of these surfaces has been pointed in figure 1 (*a*). In a previous study, Caselles and López García (1988) showed that the reflectance of these surfaces remains nearly constant from March to November. So, the images selected in this multi-temporal study were restricted to this period of time: 16 March, 22 July, 17 September and 20 November 1985.

Figure 3 shows the results of applying equation (8) to these four images. They have been paired taking the July image as a reference. All of them show the linear character of the relationship between the digital numbers of two images, whichever they are. The combination of equation (2) with the regression models given in figure 3 gives the following chlorophyll-*a* predictive equations:

For the image of March

$$\ln \mathrm{chl.}a = -0{\cdot}175 \, \mathrm{DN}_1 + 16{\cdot}8 \tag{9}$$

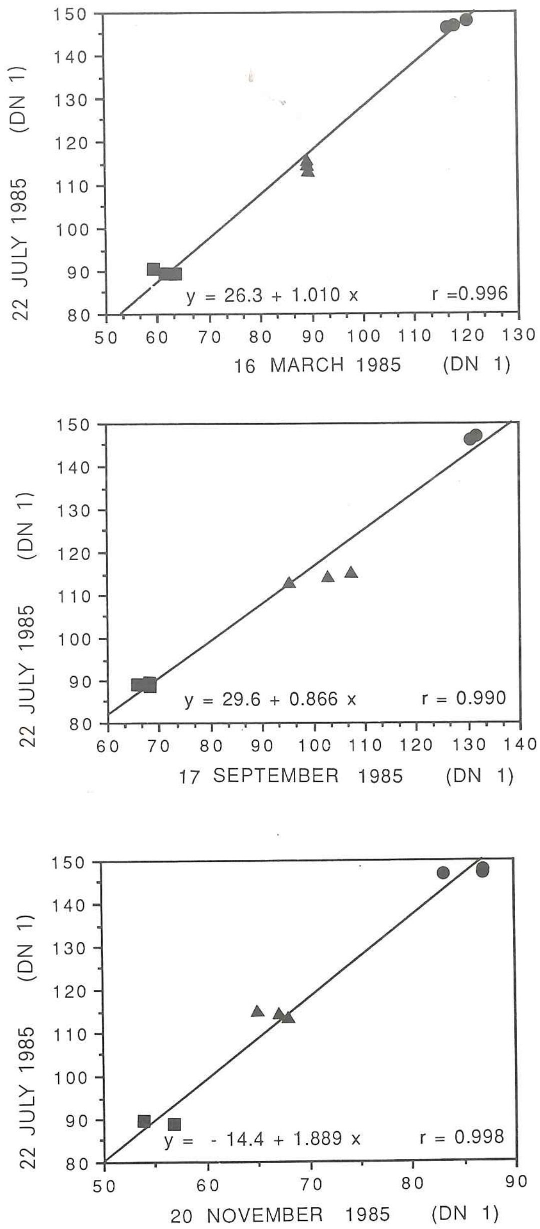


Figure 3. Correction equations obtained for 16 March, 17 September and 20 November 1985, taking July data as the image of reference. Sand (●), asphalt (▲) and sea water (■).

For the image of September

$$\ln \mathrm{chl}.a = -0{\cdot}152\,\mathrm{DN}_1 + 16{\cdot}5 \tag{10}$$

For the image of November

$$\ln \mathrm{chl}.a = -0{\cdot}333\,\mathrm{DN}_1 + 24{\cdot}2 \tag{11}$$

The images of figure 4 have been produced using these equations.

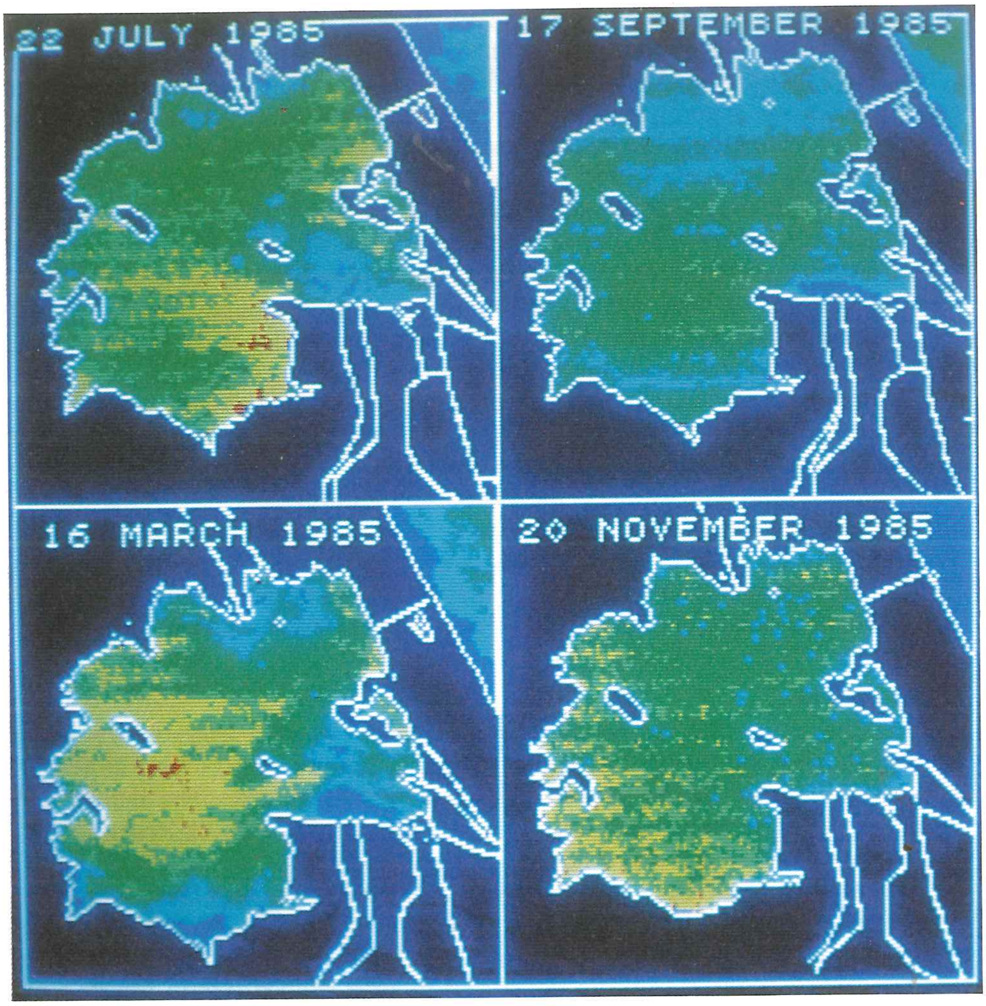


Figure 4. Maps of the chlorophyll-*a* content in the Albufera obtained from Landsat-5 Thematic Mapper band 1 for four different dates. (Red: $>750\,\mathrm{mg/m^3}$; orange: 600–$750\,\mathrm{mg/m^3}$; light green: 450–$600\,\mathrm{mg/m^3}$; deep green: 300–$450\,\mathrm{mg/m^3}$; blue: 150–$300\,\mathrm{mg/m^3}$; violet: $<150\,\mathrm{mg/m^3}$).

The validity of the proposed method is proved by the results shown in tables 2 and 3. Measured and predicted chlorophyll-*a* values have been presented both for September (table 2) and November (table 3). It can be observed that the averaged differences between measured and predicted values are about $100\,\mathrm{mg/m^3}$, which means an accuracy in chlorophyll-*a* determination of about 20 per cent (if we take $500\,\mathrm{mg/m^3}$ as the mean value in the Albufera). The values corresponding to the image of March could not be tested because *in situ* measurements were not available; however, the results seem to be quite coherent (R. Miracle, personal communication, 1988).

From the analysis of figure 4 one can determine the following:

(1) The chlorophyll-*a* distribution in the lagoon shows a high spatial variability which has not been known in previous works (Miracle *et al.* 1984). The

extraordinarily high levels of chlorophyll found are in agreement with *in situ* data, and confirm the lagoon as an extremely eutrophic ecosystem.

(2) Two different types of waters can be identified in the images, which confirm the scheme given by Soria (1987): waters coming from the channels, generally with a low biomass content and loaded with nutrient elements, and the lagoon waters which use up these nutrients and have a very high biomass content. From the images, the importance of each of these water masses has been determined. The most important flows correspond to the southern channels (Overa and Dreta), which have greater or less intensity depending on the date. Secondary to these are the contributions from the north (the Ravine of Massanassa and the Port de Catarroja) and, in some dates, the waters coming from the southwestern channels.

(3) The two major fluxes could be generating a north–south water circulation in the eastern part of the lagoon that, in addition to the flow of waters through the golas to the sea, would be responsible for the highest chlorophyll concentrations appearing in the western and southwestern parts of the lagoon, where waters become more stabilized.

(4) From this study it can be determined that the maximum chlorophyll-*a* concentration occurred in spring, with values higher than 600 mg/m^3, and the minimum values (lower than 450 mg/m^3) appear in late summer.

6. Conclusions

From the results obtained, we consider the Thematic Mapper sensor to be a useful tool for studying chlorophyll-*a* in highly eutrophic lagoons such as the Albufera of Valencia. In this case, band 1 has been chosen as the most suitable. The high ground resolution (30 m) permits one to identify in detail water masses of different quality, their extension and spatial distribution.

The multi-temporal study has been carried out without knowing the atmospheric parameters required to make atmospheric corrections, since a method of relative correction was proved. This procedure employs points where ground reflectance remains virtually constant during the period of time studied. Good results were obtained and chlorophyll-*a* concentrations have been determined from images of different dates with an error of 20 per cent. The detailed spatial distribution of chlorophyll-*a* concentrations can be determined from the images to an extent that cannot be achieved by means of sampling campaigns alone.

Acknowledgments

We thank Dr R. Miracle, Dr E. Vicente and J. M. Soria of the Departament de Ecologia, Universitat de València, for providing the surface measurements and laboratory data used in this work and their helpful comments. The financial support for this work was from the ESA (pilot projects in 1985) and from the Comisión Asesora de Investigación Científica y Técnica (Project no. A-172/85). The work was carried out while M. J. López García was in receipt of a postgraduate grant (Programa de Formación de Personal Investigador, 1985) from the Spanish Ministry of Education and Science.

References

Carpenter, D. J., and Carpenter, S. M., 1983, Modeling inland water quality using Landsat data. *Remote Sensing of Environment,* **13,** 345–352.

CASELLES, V., LÓPEZ-GARCÍA, M. J., and SORIA, J. M., 1987, Estudio del estado trófico del Lago de la Albufera (Valencia) a partir de imágenes del Landsat 5 (TM). *Proceedings of the I Reunión Científica del Grupo de Trabajo en Teledetección, held in Barcelona, Spain, on 10–11 December 1986* (Barcelona: Institut Cartogràfic de Catalunya), pp. 141–156.

CASELLES, V., and LÓPEZ GARCÍA, M. J., 1989, An alternative simple approach to estimate atmospheric correction in multitemporal studies. *International Journal of Remote Sensing,* **10,** 1127–1134.

DESCHAMPS, P. Y., HERMAN, M., TANRÉ, D., ROUQUET, M. C., and DURPAIRE, J. P., 1982, Effets atmosphèriques et evaluation du signal pour des instruments optiques de télédétection. *ESA Journal,* **82/2,** 233–246.

DESCHAMPS, P. Y., HERMAN, M., and TANRÉ, D., 1983, Modeling of the atmospheric effects and its application to the remote sensing of ocean color. *Applied Optics,* **23,** 3751–3758.

HOLYER, R. J., 1978, Toward universal multispectral suspended sediment algorithms. *Remote Sensing of Environment,* **7,** 323–338.

KHORRAM, S., 1985, Development of water quality models applicable throughout the entire San Francisco Bay and Delta. *Photogrammetric Engineering and Remote Sensing,* **51,** 53–62.

KNEIZYS, F. X., SHETTLE, E. P., GALLERY, W. O., CHETWYND, J. H., ABREAU, L. W., SELBY, J. E. A., FENN, R. W., and MCCLATCHEY, R. A., 1980, *Atmospheric Transmittance/Radiance: Computer Code LOWTRAN 5,* Environmental Research Papers, No. 697 Optical Space Division, Air Force Geophysics Laboratory, Massachusetts Air Force Systems Command, U.S.A.

LATHROP, R. G., and LILLESAND, T. M., 1986, Use of thematic mapper data to assess water quality in Green Bay and Central Lake Michigan. *Photogrammetric Engineering and Remote Sensing,* **52,** 671–680.

LILLESAND, T. M., JOHNSON, W. L., DEVELL, R. L., LINDSTROM, O. M., and MEISNER, D. E., 1983, Use of Landsat data to predict the trophic state of Minnesota Lakes. *Photogrammetric Engineering and Remote Sensing,* **49,** 219–229.

LÓPEZ-GARCÍA, M. J., and CASELLES, V., 1987, Use of Thematic Mapper data to assess water quality in Albufera Lagoon of Valencia (Spain). In *Advances in Digital Image Processing* (Nottingham: Remote Sensing Society), pp. 510–519.

MIRACLE, M. R., GARCÍA, M. P., and VICENTE, E., 1984, Heterogeneidad espacial de las comunidades fitoplanctonicas de la Albufera de Valencia. *Limnética,* **1,** 20–31.

MACFARLANE, N., and ROBINSON, I. S., 1984, Atmospheric correction of Landsat MSS data for a multidate suspended sediment algorithm. *International Journal of Remote Sensing,* **5,** 561–576.

OTTERMAN, J., and ROBINOVE, G. J., 1981, Effects of the atmosphere on the detection of surface changes from Landsat MSS data. *International Journal of Remote Sensing,* **2,** 351–360.

ROLLIN, E. M., STEVEN, M. D., and MATHER, P. M. (editors), 1985, Atmospheric corrections for remote sensing. *Proceedings of a Remote Sensing Workshop on Atmospheric Corrections, held in Nottingham, England, on 22 May 1985.* (Nottingham: Remote Sensing Society), pp. 4–10.

ROSSELLÓ, V. M., 1979, Els espais albuferencs del País Valencià. *Acta Geológica Hispánica (Homenatge a Lluis Solé Sabarís),* **14,** 487–493.

SORIA, J. M., 1987, *La Eutrofización de la Albufera de Valencia: Mineralización, Nutrientes y Biomasa,* Masters dissertation, Universitat de València, Spain.

STRICKLAND, J. D. H., and PARSONS, T. P., 1968, *A Practical Handbook of Seawater Analysis,* Bulletin of the Fisheries Research Board of Canada, No. 167 (Ottawa: Fisheries Research Board).

TANRÉ, D., DEROO, C., BUHAUT, P., HERMAN, M., MORCRETTE, J. J., PERBOS, J., and DESCHAMPS, P. Y., 1986, *Simulation of the Satellite Signal in the Solar Spectrum (5S)* (Villeneuve d'Asq: Laboratoire d'Optique Atmosphérique Université des Sciences et Techniques de Lille).

TURNER, R. E., and SPENCER, M. M., 1972, Atmospheric model for the correction of spacecraft data. *Proceedings of the Eighth International Symposium on Remote Sensing of Environment held in Ann Arbor, on 2–6 October 1972* (Ann Arbor: Environmental Research Institute of Michigan), pp. 895–934.

VERDIN, J. P., 1985, Monitoring water quality conditions in a large Western reservoir with Landsat imagery. *Photogrammetric Engineering and Remote Sensing,* **51,** 343–353.