Multitemporal Analysis of "Simultaneous" Landsat Imagery (MSS and TM) for Monitoring Primary Production in a Small Tropical Coastal Lagoon

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Abstract
The net primary production (NPP) of surface water in the Coyuca de Benitez coastal lagoon was studied from 1981 to 1991. Landsat imagery acquired "simultaneously" with in situ *data was processed in a PC-based system to obtain the NPP Thematic Maps Generated by Correlation (TMGC). Three dates were considered: Summer 1981, Summer 1987, and Winter 1988–89. The determination coefficients* (R^2) *of the best seasonal regression models were high, from 0.98 to 0.99. P-values ranged from 0.0003 to 0.0057. Accuracy Indices (i.e., percentage of well-classified sampling points) of the best multiband classified NPP thematic maps were 80 percent for 1981 (100 percent considering only lagoon sample points) with MSS data; and 80 percent for 1987 and 90 percent for 1989, both with TM data.*

Introduction
In the literature regarding water quality assessment by satellite remote sensing, indices such as turbidity, algal pigments concentration, salinity, chlorophyll-*a*, total suspended solids, Sechhi disk depth, and surface temperatures (Carpenter and Carpenter, 1983; Khorram, 1985; Khorram and Cheshire, 1985; Lathrop and Lillesand, 1986; Lathrop and Lillesand, 1989; Ritchie *et al.*, 1990) in different types of water bodies (freshwater lakes, bays, deltas, and estuaries) have been studied. Other research in Mexican coastal lagoons, in addition to the present study in Coyuca de Benitez, Guerrero, includes a study reported of suspended sediment in Laguna de Términos with non-simultaneous imagery (Jensen *et al.*, 1989).

The dynamics of the Coyuca de Benitez coastal lagoon have been studied from 1981 to 1991 by using *in situ* and remote data (Ruiz-Azuara *et al.*, 1983a; Ruiz-Azuara *et al.*, 1983b; Ruiz-Azuara, 1985a; Ruiz-Azuara, 1985b; Aguirre *et al.*, 1989; Ruiz-Azuara *et al.*, 1989; Pérez *et al.*, 1989; Ruiz-Azuara and Pérez, 1992; Ruiz-Azuara, 1992a; Ruiz-Azuara, 1992b).

The main goal of this project was to evaluate the usefulness of remote sensing data for modeling and monitoring water quality in a small tropical coastal lagoon.

Several hydrobiological parameters were analyzed: net primary production, chlorophyll-*a*, Sechhi disk depth, pH, water temperature, total suspended solids, phytoplankton, zooplankton, salinity, and nutrients, at different seasons.

In this paper, a methodology for the multitemporal monitoring of the surface water net primary production in a small tropical coastal lagoon is presented. It includes the use of acquired "simultaneous" high resolution multispectral remote sensing imagery and *in situ* data. NPP Multiband TMGCs were used as a tool for monitoring NPP temporal changes.

Data Sources
From 1981 to 1991, different data sources were considered. Analog and digital remote images, both aerial and spatial, were analyzed.

Seasonal variations of water net primary production (NPP) (mg/l hr) during an annual cycle (Summer 1981—Spring 1982) were studied (Ruiz-Azuara *et al.*, 1983a). Non-simultaneous imagery was acquired, with a maximum delay of 11 days. Aerial black-and-white infrared photography and multispectral images acquired with the Daedalus Model AADS1280 scanner, corresponding to summer and winter, were available. Summer data were useful to show superficial currents. The high resolution (6-m) digital images for summer showed the capability to separate water classes with different concentrations of chlorophyll-*a* (Ruiz-Azuara *et al.*, 1983b). The preliminary results were promising (Ruiz-Azuara, 1985b), but the high resolution airborne imagery was no longer available. Under this situation, Landsat imagery had to be considered as an alternative.

For summer 1981, a Landsat 3 multispectral image was acquired on 1 August. Sampling data for 31 July and 1 August 1981 were available. Statistical models obtained by multiple linear regression between both sets of remote and *in situ* data showed high coefficients of determination with high levels of significance (Ruiz-Azuara, 1985).

For summer 1987 and winter 1988-89, "simultaneous" TM Landsat images were acquired.

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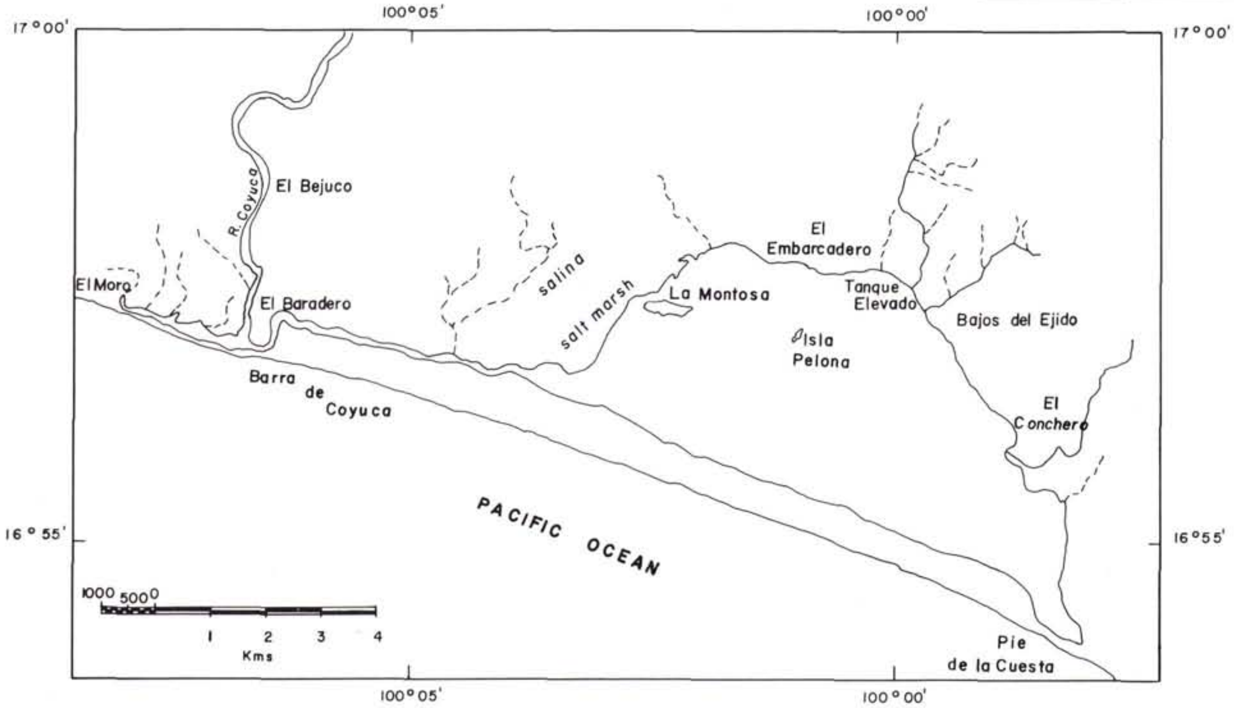

Figure 1. Map of Coyuca de Benitez, Guerrero Coastal Lagoon.

Thematic Maps Generated by Correlations (TMGC)

Monoband Thematic Maps Generated by Correlation (TMGC) corresponding to "simultaneous" remote and *in situ* data were introduced as a tool for multitemporal monitoring (Ruiz-Azuara *et al.*, 1989). The PC-based system used the MICROPIPSEGA.1 software (The Telesys Group, 1987) that works with integer coefficients. Thematic maps calculated under this restriction successfully represented only the mean values. The studied water quality parameters were chlorophyll-*a*, pH, salinity, total suspended solids, nitrites, and temperature. New products were implemented to recover zonation. Multiband Thematic Maps Generated by Correlation were introduced for monitoring salinity in a holigohaline coastal lagoon (Ruiz-Azuara and Pérez, 1992; Ruiz-Azuara, 1992a).

Study Area

The Coyuca de Benitez coastal lagoon is located in the state of Guerrero (Detenal, 1981), southwestern México, bounded by the Pacific Ocean (see Figure 1). It is ≈20 km from Acapulco. The lagoon covers an approximate area of 34 km^2 (Yañez-Arancibia, 1978; Klimek, 1978). The lagoon has contributions of fresh-water from the main tributaries—the Coyuca River and the Las Cruces rivulet—and also of sea water when the sand bar is opened (Figure 1). The type of vegetation around the lagoon consists of tropical forest over a flat land matrix, with associations of tule, reed-grass, mangrove tree, huisachal, and palm trees (Guzmán, 1976).

Methodology

During the period of time between 1981 and 1991, we were developing and implementing the methodology in Figure 2. The main goal of this project was to evaluate the usefulness

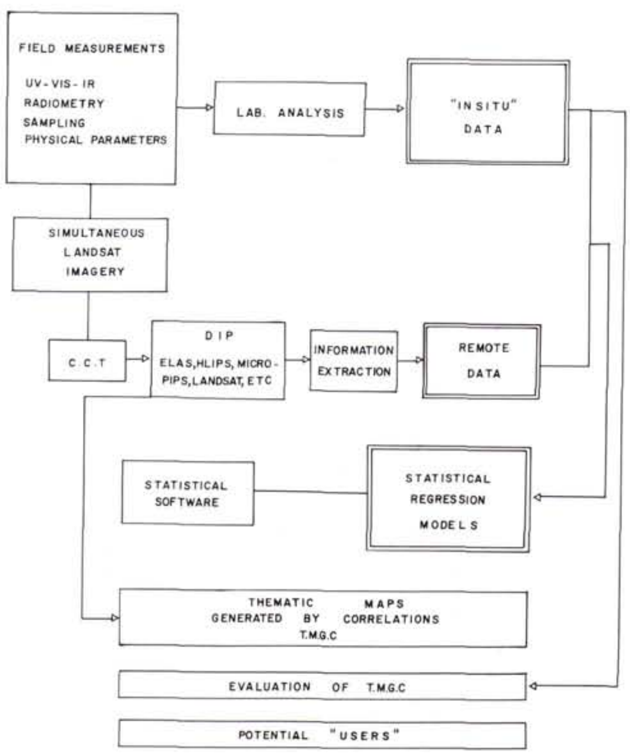

Figure 2. Methodology.

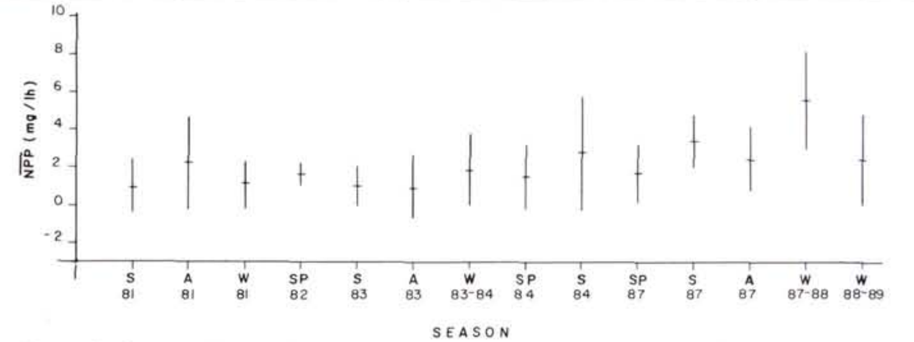

Figure 3. Seasonal variations of the mean net primary production. Bars represent the standard deviation.

of the available remote sensing imagery for modeling and monitoring water quality parameters in a small tropical coastal lagoon. The following specific tasks were developed:

- The obtaining of correlations between the water quality parameters for the real system and the information extracted from the digital images; in other words, learning about the contributions of the different spectral bands (including principal components) to each water quality parameter in a specific date.
- The selection of the best multiple regression models. Variance analysis criteria were applied.
- The production of synthetic images called Thematic Maps Generated by Correlation (TMGC) for each water quality parameter modeled for different seasons.
- The comparison of both predicted values and Thematic Maps with *in situ* data.

The "simultaneous" sampling and acquiring of the remote imagery (MSS and TM Landsat in this case) is vital to this methodology. Also, measurements of UV-VIS-IR radiometry were taken at each sample point in order to obtain the reflectivity coefficient and the portion of emergent radiation. These results will be reported separately. The *in situ* water samples were analyzed in the UNAM laboratories. The acquisition of the "simultaneous" Landsat images becomes very complicated in a country like México without a ground station for direct reception. The TM scene must be ordered and paid for in advance. Once the image is recorded, it is necessary to wait for a printed picture in order to be sure that the area of interest was free of clouds and the image had the required quality. Finally, after three or four months, the image is received in a CCT format. The tropical coastal zone has clouds most of the time. It is a real limitation for the visible and near-infrared imagery. During the Spring 1987 to Winter 1987-88 cycle, all four TM images were cloudy, but the image corresponding to Summer 1987 could be used because the clouds affected only the southeast sampling points (i.e., points 1, 2, and 3). All Landsat images were ordered geometrically and radiometrically corrected.

The digital images that are analyzed in this paper were processed in two stages. The full image (for MSS) or the quarter of an image with the area of interest (for TM) was displayed with the HLIPS at the IBM Scientific Center of México, and a sub-scene of 640 by 480 pixels was recorded on a CCT. This was transferred to diskettes in the UNAM Academic Computer Center. The sub-scene was processed with Landsat Image Processor Version 4.4 (Loomer, 1988), MICROPIPSEGA.1 (The Telesys Group, 1987), and MICROPIPSEGA.2 (The Telesys Group, 1988). Georeferencing was not considered necessary at this stage. The region is very small, the training fields very large (7 by 7 pixels), and the images will not be superimposed. The sampling points were positioned by triangulation, both in the field and in the image. Relevant points, easy to identify, were taken as reference.

Due to the presence of water as the main component of the TM sub-images, we applied a simple atmospheric correction. Before we extracted information from the selected training fields, the histograms of bands 1 to 4 were shifted to 0 gray level (Schowengerdt, 1983; Sabins, 1987). The spectral information was extracted for training fields (7 by 7 pixels) corresponding to the sampling points. After that, the "simultaneous" data were ready. We used quotation marks (" ") to note that the *in situ* data were not taken at exactly the same time, but on the same day with some difference in time, from a few minutes to three hours, due to equipment restrictions (one boat and one portable radiometer). The radiometric measurements (taken with an IL700/760/784 spectroradiometer) and the sampling data were taken simultaneously.

The values of net primary production were obtained by applying the Winkler technique and the formulas proposed by Wetzel and Likens (1979) in order to transform the dissolved oxygen concentrations to values of net primary production. The units are mg l^{-1} hr^{-1}. Seasonal variations of mean NPP values (and standard deviation) measured from 1981 to 1989 are shown in Figure 3.

Once the mean values of the digital numbers at the training fields, R_is and the *in situ* data P_is, were obtained, the simple and multiple linear regression models were calculated. The statistical software available was the Statistical Graphics System (Statgraphics) and the Statistical Package for the Social Sciences (SPSS).

The R_is and their ratios C_{ij}s; the principal components PC_is and their ratios CPC_{ij}s; and the sampling hour, H_s, were considered as predictor variables. The multiple regression NPP selected models and their statistical summaries are presented in Table 1. Variance analysis criteria were used.

The ranges of *in situ* NPP data corresponding to those models are in Table 2. The best simple regression NPP models with all predictor variables were calculated. The four highest correlation coefficients corresponding, respectively, to R_is, C_{ij}s, PC_is, and CPC_{ij}s were considered and their images were displayed. The three best were selected. Under similar conditions, bands (R_is and PC_is) have priority over ratios (C_{ij}s and CPC_{ij}s).

TABLE 1. NPP SELECTED MODELS AND STATISTICAL SUMMARIES.

Summer 81		
$NPP \cong -0.97\ (0.01)\ R_1 - 3.74\ (0.02)\ R_2 - 3.96\ (0.02)\ C_{34} + 79.22$		
$R^2 = 0.9999$	Adj. $R^2 = 0.9999$	D.F. = 3/1
F = 74731	P-Value = 0.003	S.E.E. = 0.0051
Summer 87		
$NPP \cong 0.59\ (0.36)\ C_{12} + 4.67\ (0.04)\ R_6 + 6.24\ (0.08)\ R_5 + 104.32\ (1)\ C_{23} - 24.07\ (0.24)\ C_{57} + 3.79\ (0.41)\ R_1 - 18.59\ (0.22)\ C_{24} - 742.48$		
$R^2 = 0.9999$	Adj. $R^2 = 0.9996$	D.F. = 7/2
F = 3466.81	P-Value = 0.0003	S.E.E. = 0.0274
Winter 88-89 (20)		
$NPP \cong -3.47\ (0.82)\ C_{17} - 0.16\ (0.08)\ H_s + 68.02\ (45.86)\ C_{36} + 8.33$		
$R^2 = 0.7400$	Adj. $R^2 = 0.6706$	D.F. = 4/15
F = 10.67	P-Value = 0.0003	S.E.E. = 0.6767
Winter 88-89 (10)		
$NPP \cong 5.25\ (0.49)\ R_7 - 3.53\ (0.43)\ R_5 + 6.23\ (1.06)\ R_3 - 4.97\ (0.75)\ R_4 - 1.81\ (0.44)\ R_2 + 0.21\ (0.11)\ R_6 - 27.19$		
$R^2 = 0.9879$	Adj. $R^2 = 0.9639$	D.F. = 6/3
F = 41.08	P-Value = 0.0057	S.E.E. = 0.2297

TABLE 2. SIMULTANEOUS "*in situ*" NPP DATA.

Season	(# sample points)	NPP	NPP_{max}	NPP_{min}	St. Dev.
Summer	81 (5)	0.3476	1.624	−1.503	1.2180
Summer	87 (12)	3.3565	5.600	1.218	1.4560
Winter	88-89 (20)	2.3958	4.467	0	1.1788
Winter	88-89 (10)	2.4282	4.345	0	1.2089

With the best single and multiple statistical regression models (linear or logarithmic), the multiband Thematic Maps Generated by the Correlations (TMGC) were obtained. Restrictions on available software influenced the generation of these synthetic images. For instance, the Image Algebra module of MICROPIPSEGA works with integer coefficients. As a consequence, the synthetic image corresponding to the best multiple regression model is only an approximation of the theoretical model. For this reason, even with a good statistical model, the monoband TMGC could well represent the mean value of the modeled parameter, but not always its zonation. With the best simple regression models, this zonation is recovered.

To obtain multiband TMGCs, the following criteria were considered:

- A monoband TMGC corresponding to the best multiple regression model, as a good representative of the mean value (Ruiz-Azuara *et al.*, 1989) should be included.
- The simple regression models, as a representation of the most correlated predictor variables, should be included. Due to limitations of Landsat Image Processing software, no more than three simple regression models can be considered.
- The selected algorithm for classification was maximum likelihood.

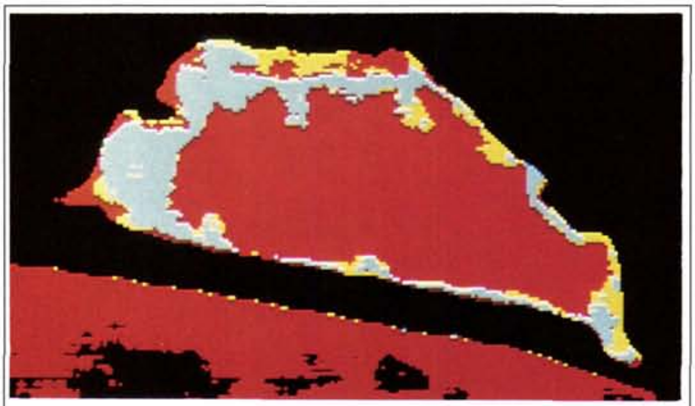

Plate 1. Summer 81 NPP TMGC.

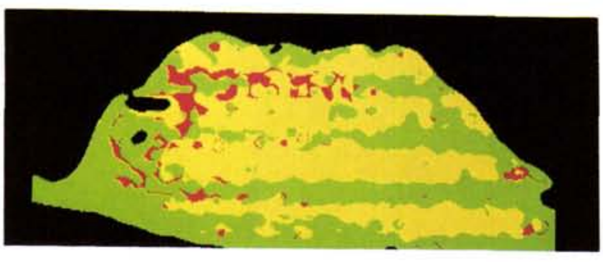

Plate 2. Summer 87 NPP TMGC.

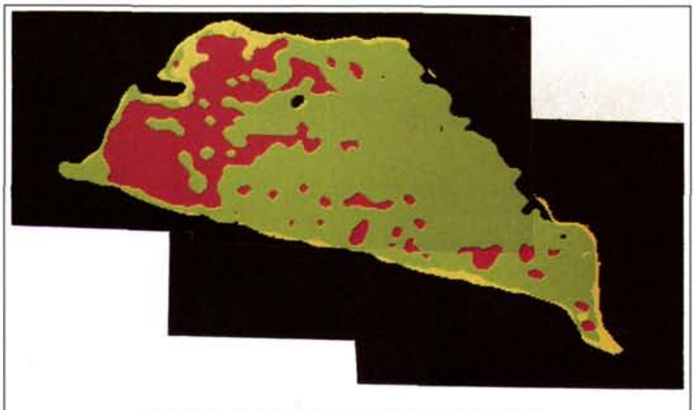

Plate 3. Winter 88-89 (20P) NPP TMGC.

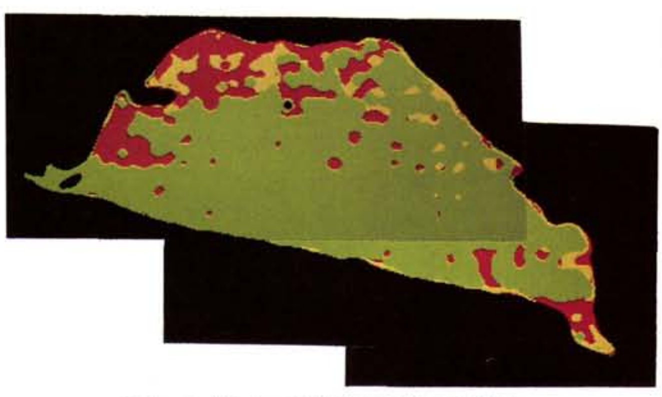

Plate 4. Winter 88-89 (10P) NPP TMGC.

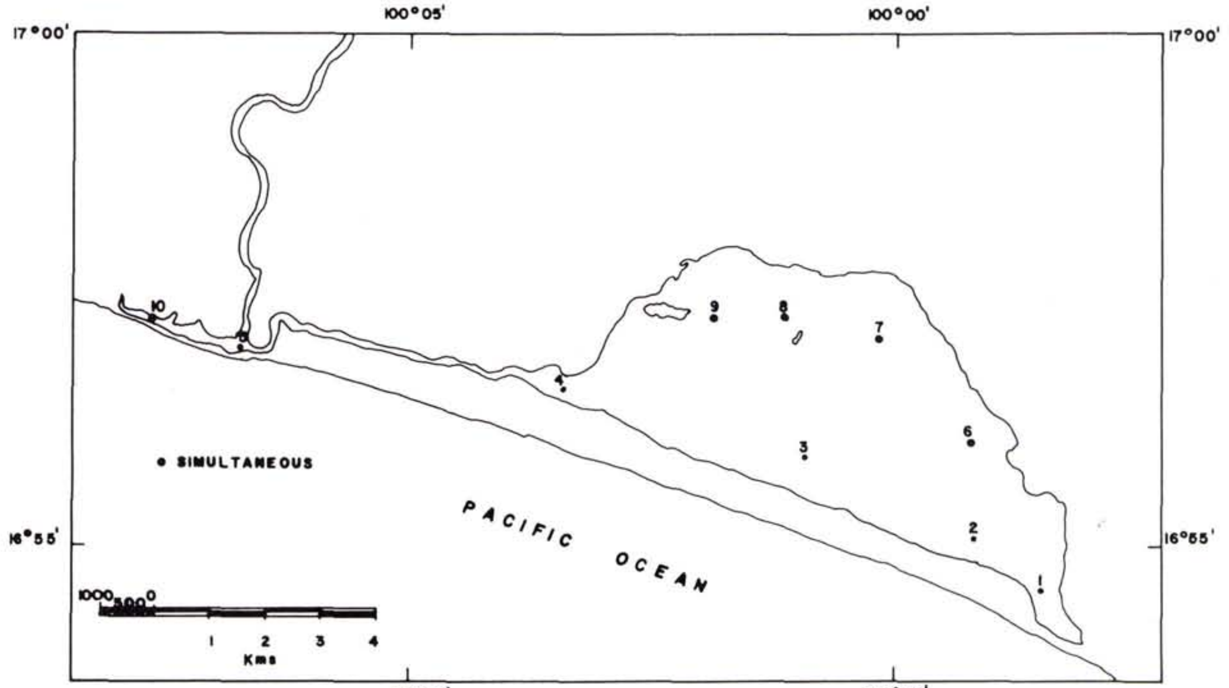

Figure 4. Summer 81 sample points.

- A 5 by 5 or 7 by 7 median filter can be applied to improve the TMGC's visual quality. These values are related to the size of the Landsat Image Processor training samples (7 by 7 pixels).
- The accuracy of TMGCs is measured with respect the ground truth data (Gunther and Rose, 1987). An Accuracy Index (AI) is defined as

$$\text{AI}\ (\%) = \frac{\#\ \text{sampling points well-classified}}{\#\ \text{total of sampling points}}$$

In summary, to produce the multiband TMGCs, the specific steps are

- Obtain the multiple and simple regression models.
- Select the best multiple and simple models.
- Calculate the synthetic image for the best multiple regression model.
- Review the characteristics of its quality.
- Select the best simple regression models.
- Display them and choose the three best.
- Apply a median filter to all chosen bands (if necessary).
- Define the different classes according to the ranges of *in situ* data.
- Extract statistics of the selected bands.
- Select the best training fields.
- Run the maximum-likelihood algorithm with the different bands and combinations and select the classification with highest AI (Accuracy Index, i.e., percentage of well-classified sampling points).
- Choose the final colors for classes and proceed to prepare the multiband TMGCs for all involved dates.

By using the above sequence, the TMGCs corresponding to NPP81 (Plate 1), NPP87 (Plate 2), and NPP89 (Plates 3 and 4) were calculated.

The resulting TMGCs were evaluated with respect to the field data and compared with the traditional NPP isoline maps. The usefulness of the multitemporal TMGCs required the selection of common classes and colors for easy analysis of the evolution of the water body during the period 1981-1989. Net primary production values measured from 1981 to 1989 varied within the interval from −2 to 10 mg/l hr. The negative value was detected in the Coyuca River. A second limitation of the Landsat Image Processor Version 4.4 (Loomer, 1988) is the number of classes (six) considered for classification. As a consequence, the NPP interval was sliced into the following six classes: −2 to 0, 0 to 2, 2 to 4, 4 to 6, 6 to 8, and 8 to 10. The range of each class was arbitrarily adopted equal for generality. The particular color assigned to each one of these classes was fixed for all the period 1981–1989. A median filter was applied to the bands considered in the classification in order to improve the aspect of the thematic maps caused by the striping of the Landsat images. The final products, the NPP thematic maps, let potential users follow the behavior of the net primary production during the period of interest. The methodology described was also applied to the remaining hydrobiological parameters. These results are being reported separately.

Results

The results of this research are presented for three different dates: Summer 1981, Summer 1987, and Winter 1988-89.

Summer 1981

The bar was open at that time. Ten sample points were chosen (Figure 4). Five points were sampled "simultaneously" with the Landsat MSS image on 1 August 1981 (points 6 to 10). The other five (points 1 to 5) were sampled the day before. Two points were selected out of the lagoon (P5 and P10). They are in the Coyuca River, with Point 5 correspond-

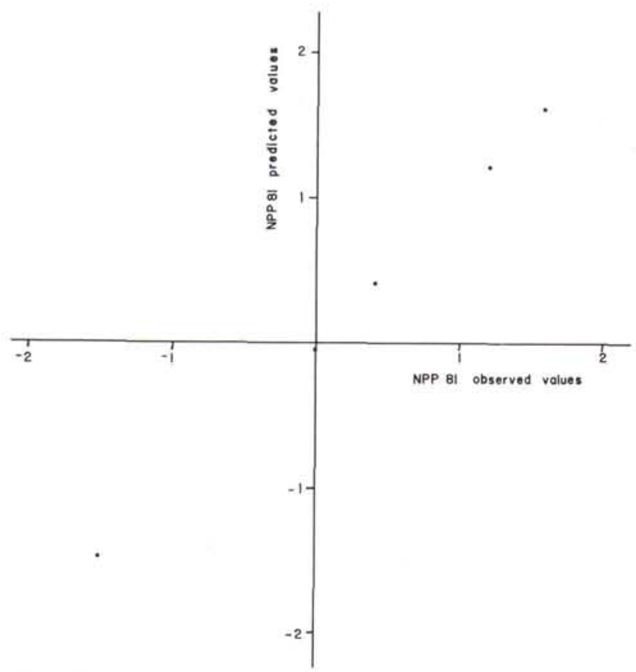

Figure 5. NPP81 predicted values versus NPP81 observed values.

ing to the sand bar. Point 4 is in the mouth of the river. Point 1 is in front of an inhabited area and points 8 and 9 are between currents, one coming from the sea or from the Coyuca River (through the channel) and the others from small tributaries. These superficial currents were observed with aerial black-and-white infrared photography and with aerial multispectral imagery for the same season (Ruiz-Azuara *et al.*, 1983a; Ruiz-Azuara *et al.*, 1983b). The approximate depth of points 3, 7, 8, and 9 was 9 m. The mean depth of the other six points was 2.26 m. The Sechhi Disk depth was very small, from 30 to 35 cm. The results obtained for three depths—superficial, 0.5 m, and 1 m—show homogeneity in the water column. The ranges of the *in situ* net primary production (NPP) data taken simultaneously with the satellite Landsat data are shown in Table 2. The negative values during Summer 1981 occurred at Point 10, in the Coyuca River, not in the Lagoon.

The best correlation coefficients (absolute value) for the simple linear regression between NPP and the predictor variables were 0.9636 (R_2), 0.9597 (C_{34}), 0.9164 (H_s), and 0.8090 (PC_1). The highest absolute value was 0.9636 with MSS band 2, which included a chlorophyll-*a* absorption peak. The selected multiple regression model corresponding to Summer 1981 and its statistical summary are presented in Table 1. The plot of NPP predicted values versus NPP observed values is shown in Figure 5. The fit is very good. The map of superficial NPP isolines for field data is in Figure 6.

The NPP multiband TMGC produced with the 1981 image is shown in Plate 1. It is a three-band (best multiple regression, R_2, and PC_1) classified map showing three classes: NPP −20 (−2 to 0 mg/l hr), NPP 02 (0 to 2 mg/l hr), and NPP 46 (4 to 6 mg/l hr). The thematic map shows low production in the region with currents, the west zone; medium values (near NPP mean value from Figure 4 considering the eight sample points in the lagoon and including NPP mean values from Table 2 for the five simultaneous sample points) in the center of the lagoon; and maximum values in the inner shoreline. The Accuracy Index (AI = percentage of well-classified sampling points) of the NPP thematic map for the eight sample points inside the lagoon (four of them were not used for modeling) is 100 percent. The NPP thematic map also shows the effect of the opened sand bar, as Plate 1 makes evident. For this reason, the chosen scale is different from the other NPP thematic maps. Due to the resolution of around 80 m for the MSS images, it is meaningless to try to predict the values of the sample points situated in the Coyuca River because the river is narrower than the pixel resolution. Therefore, an Accuracy Index of 80 percent was obtained for the ten Summer sample points. In this case, the remaining 20 percent could not be considered a failure of the model but the effect of the small resolution of the MSS images.

The comparison of the traditional NPP isolines map in Figure 6 with the Summer 1981 NPP Thematic Map in Plate 1 requires consideration of the ranges in the selected classes. The apparent two water masses from 0 to 1 and from 1 to 4 are not evident in the thematic map, because of the different ranges of the classes. In order to obtain a specific comparison with the isolines map, the selected classes should be changed to $0 < \text{NPP} < 1$ and $1 < \text{NPP} < 4$. This map is not presented here because the exact reproduction of each one of the isoline maps was not in our objectives.

Summer 1987

The night before the sampling day, it was raining. The day of the sample started out cloudy and became clear later. The 17 August TM image showed clouds only over one zone of the lagoon, covering mainly three sample points: 1, 2, and 3. In spite of this problem, that image was the only useful one for the 1987 seasonal cycle, as we mentioned before. From the 15 sample points chosen (Figure 7), ten were used for the regression model: 4, 6, 7, 8, 9, 13, 15, 16, 17, and 18. All of them were sampled "simultaneously" with the TM Landsat image acquisition on 17 August 1987. With ten sample points selected, free of clouds, the simple and multiple regression models were calculated.

The best correlation coefficients (absolute value) for the simple linear regression between NPP and the predictor variables were 0.4148 (C_{12}), 0.4086 (CPC_{46}), and 0.3502 (PC_5). The highest absolute value was 0.4148 with $C_{12} = R_1/R_2$ for TM bands 1 and 2. The selected multiple regression model corresponding to Summer 1987 and its statistical summary are presented in Table 1. It has a high coefficient of determination (0.99) and high significance, with a P-value of 0.0003. The ranges of the *in situ* NPP data taken simultaneously with the TM image are shown in Table 2. In general terms, the NPP is larger than the corresponding values for Summer 1981 (see Figure 3). The plot of NPP predicted values versus NPP observed values is shown in Figure 8. It suggests good concordancy in spite of the large number of terms in this model. The NPP isolines map based on the field data is presented in Figure 9.

The NPP multiband TMGC produced with the 1987 image is shown in Plate 2. It is a four-band (best multiple regression, C_{12}, CPC_{46}, and PC_5) classified map showing three classes: NPP 02 (0 to 2 mg/l hr), NPP 24 (2 to 4 mg/l hr), and NPP 46 (4 to 6 mg/l hr).

The thematic map showed the lowest production in the region with currents, the west side, as in the thematic map

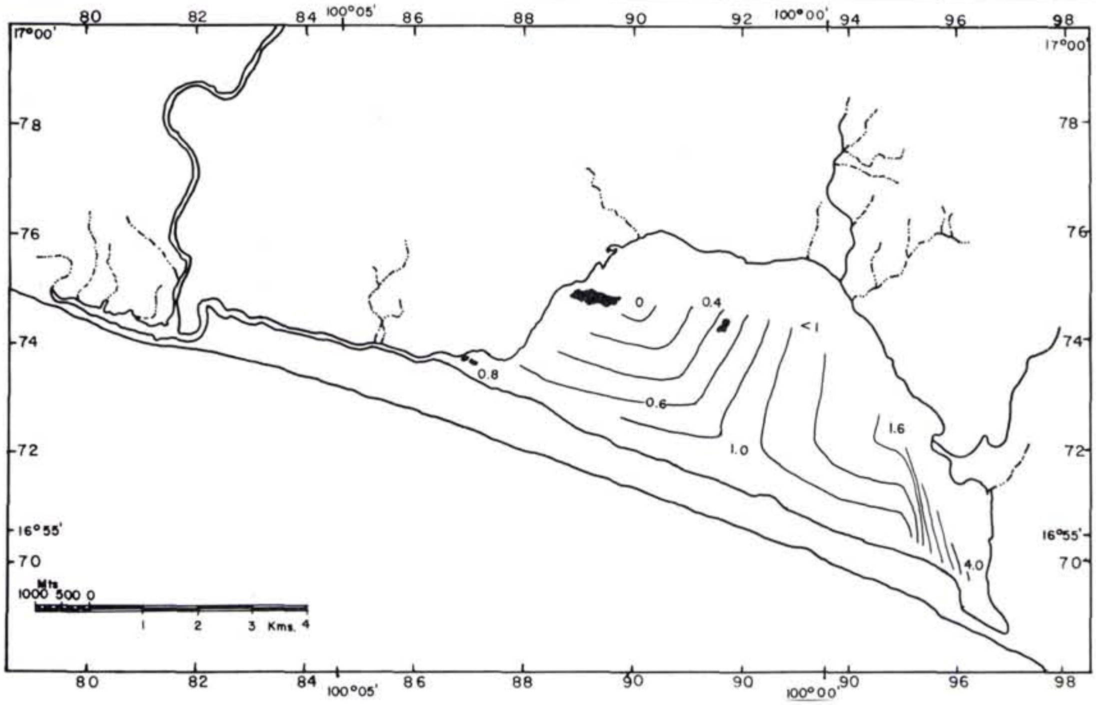

Figure 6. Summer 81 NPP isolines map.

corresponding to the 1981 image, but the value of this low production corresponds to the medium value during the Summer 1981. The second class is located mostly in the outer shoreline, and the maximum values corresponded to the center and inner shoreline. The Accuracy Index of this thematic map for the ten modeled sample points is 80 percent. If the best seven training fields (i.e., those with a lower standard deviation) are selected, the remaining sampling points are also well classified. The Accuracy Index could rise to 100 percent. That climate conditions affected the homogeneity of the lagoon and the mixture of the different classes is clear in the resulting NPP thematic map (Plate 2). The increase in the mean value of NPP 1987 with respect to the mean value of NPP 1981 is evident from the correspond-

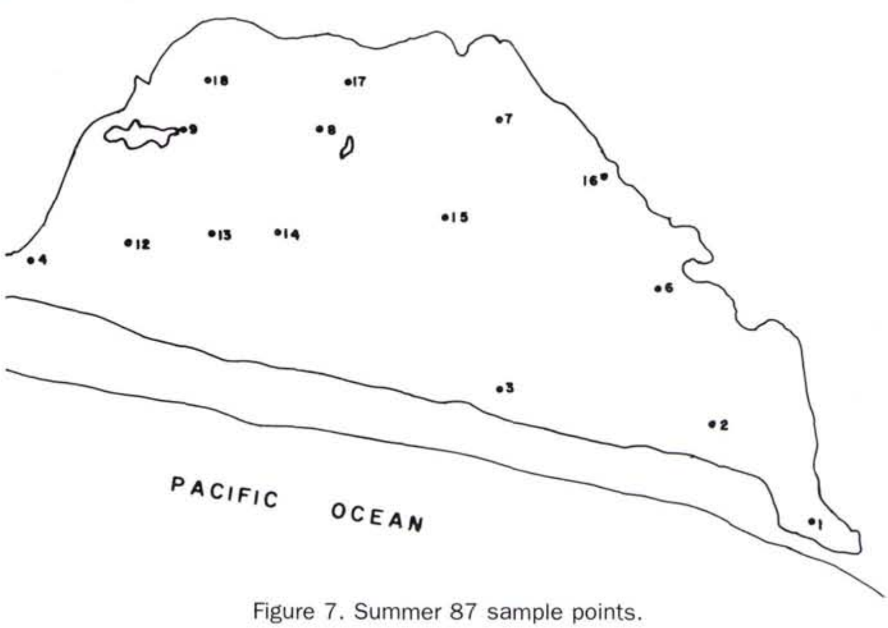

Figure 7. Summer 87 sample points.

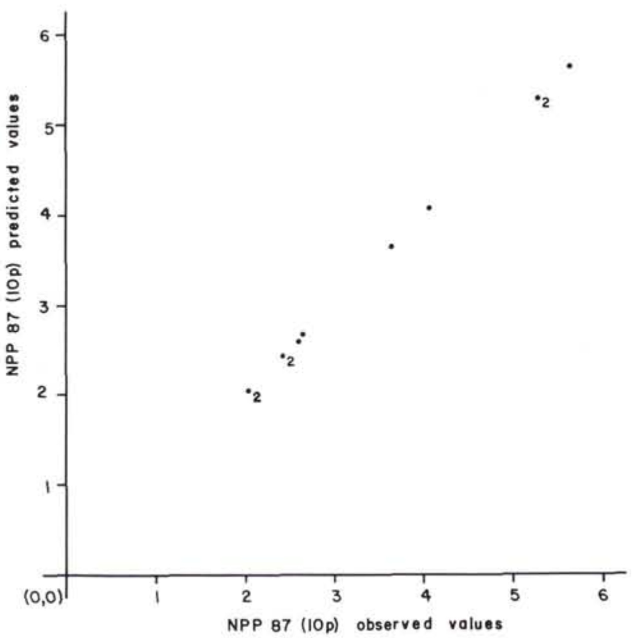

Figure 8. NPP87 predicted values versus NPP87 observed values.

ing thematic maps if Figure 7 and Plate 2 are compared. The presence of horizontal banding in the thematic map corresponding to 1987 is in part due to the striping in the original TM image, but the isolines map (Figure 9) also suggests this kind of behavior.

Winter 1988-89

On 18 January 1989, a cloud-free TM image for the zone of the lagoon was acquired. The radiometric equipment and the general methodology was improved, reducing sampling time, and 20 points were sampled "simultaneously" with the Landsat satellite passing over the Coyuca de Benitez lagoon. The sampling points are marked in Figure 10. Two kinds of models were obtained for this season: a 20-point model and a 10-point model. Both gave valuable information. With the 10-point model, we chose a set including the original eight points considered during Summer 1981 for easier comparison of common zones in the multitemporal approach. Also, it was possible to evaluate the predictivity of the statistical model in the ten points that were not modeled. The 20-point model gave information over new zones that were not modeled before, and it is more representative from the statistical point of view. Finally, by comparing both NPP thematic maps, information about the sensitivity of the statistical models with the set of sampling points selected could be obtained for this water body. The ten points selected are 1, 2, 3, 4, 6, 7, 8, 9, 12, and 13 from Figure 10. The mean value on NPP for both the 20 and 10 sets of sample points is almost the same as shown in Table 2.

The best correlation coefficients (absolute value) for the simple linear regression between NPP20 and the predictor variables were 0.7592 (C_{17}), 0.6493 (CPC_{25}), 0.5512 (R_1), and 0.5042 (PC_5). The highest absolute value was 0.7592 with $C_{17} = R_1/R_7$. The selected multiple regression model NPP20, corresponding to Winter 1988-89, and its statistical summary are shown in Table 1. The plot of NPP20 predicted values versus NPP20 observed values is shown in Figure 11. The ad-

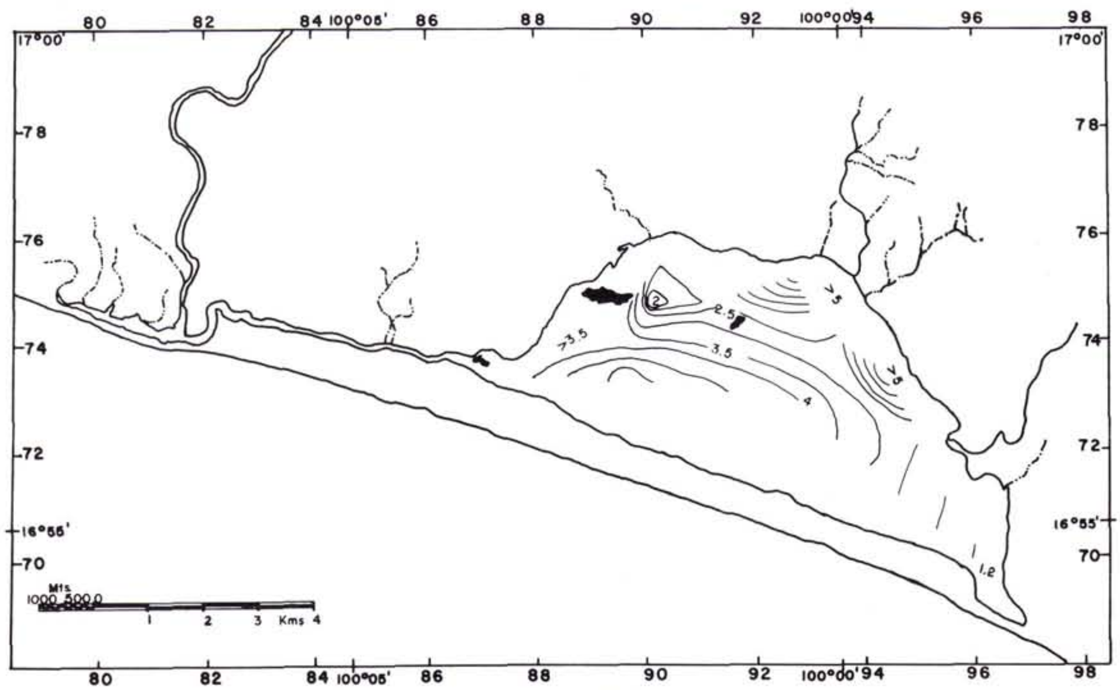

Figure 9. Summer 87 NPP isolines map.

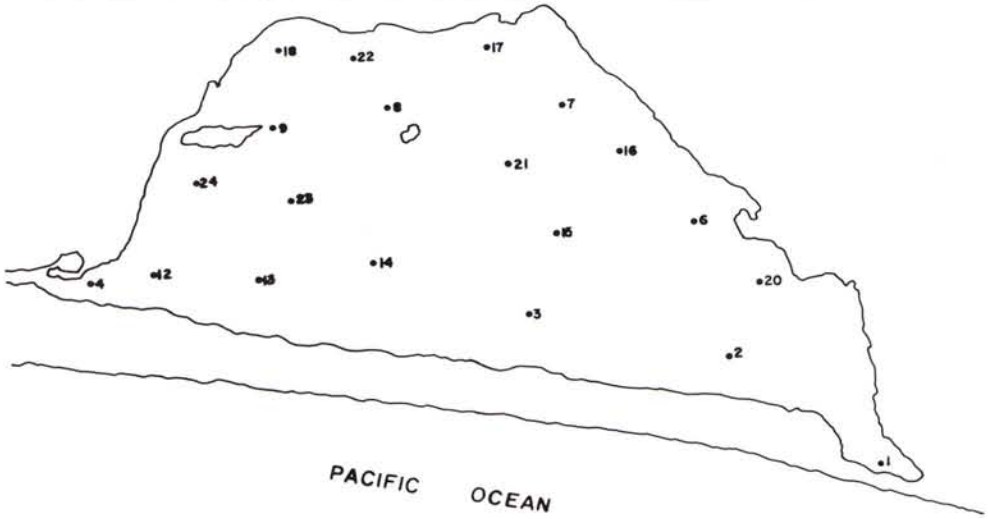

Figure 10. Winter 88-89 sample points.

justed determination coefficient of this correlation is only 0.67. The points show some dispersion. The NPP isolines map for Winter 1988-89 field data is in Figure 12.

The Winter 1988-89 NPP20 multiband TMGC is shown in Plate 3. It is a four-band (best multiple regression, C_{17}, PC_5, and R_1) classified map showing three classes: NPP 02 (0 to 2

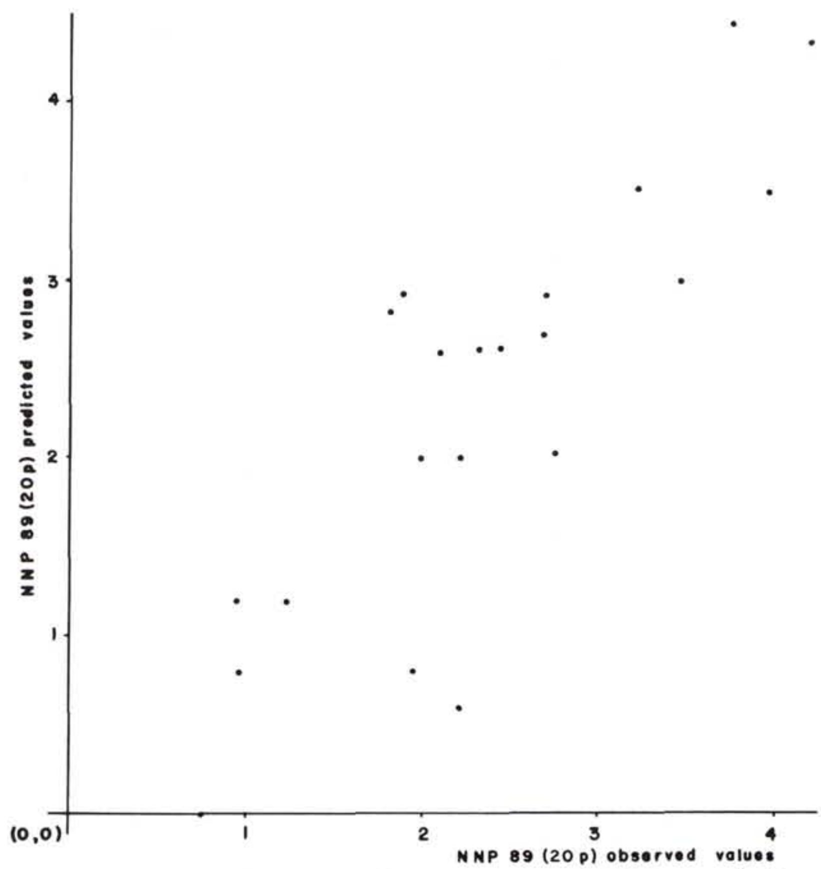

Figure 11. NPP89 (20P) predicted values versus NPP89 (20P) observed values.

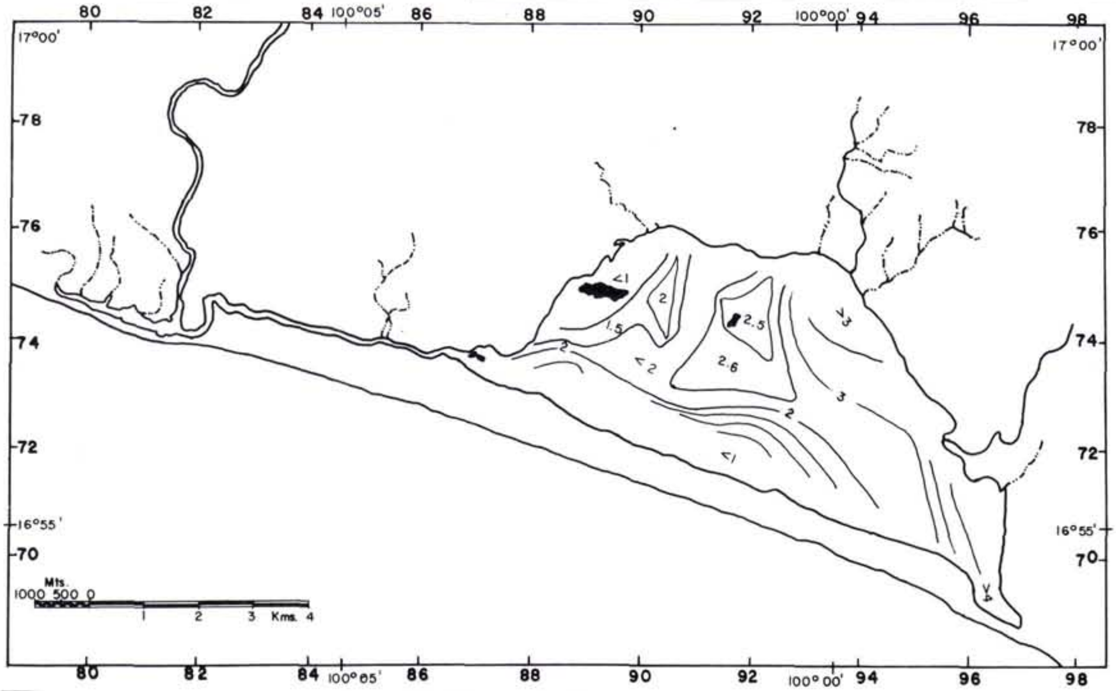

Figure 12. Winter 88-89 NPP isolines map.

mg/l hr), NPP 24 (2 to 4 mg/l hr), and NPP 46 (4 to 6 mg/l hr). This thematic map shows an extended low production zone on the west side. The value of the low production here corresponded to the medium values for Summer 1981. The dominant class was the medium with NPP from 2 to 4 mg/l covering the right side, except for the extreme right at the Pie de la Cuesta zone and to the north of the La Montosa Island, which presented higher NPP values (from 4 to 6 mg/l). The Accuracy Index of the NPP20 thematic map was 90 percent.

The best correlation coefficients (absolute value) for the simple linear regression between the NPP10 set of points and the predictor variables were 0.7826 (C_{13}), 0.6888 (R_7), 0.6789 (PC_5), and 0.6555 (CPC_{15}). The highest absolute value was 0.7826 with $C_{13} = R_1/R_3$. The selected NPP10 multiple regression model corresponding to Winter 1988–89 and its statistical summary are presented in Table 1. The plot of NPP10 predicted values versus NPP10 observed values is shown in Figure 13. The adjusted determination coefficient of this correlation is 0.96. The dispersion is reduced with respect to the 20-point model. The NPP10 multiband TMGC produced with the 1989 image is shown in Plate 4. It is a two-band (best multiple correlation and R_7) classified map showing the same three classes as the NPP20. The general behavior was similar to the NPP20 thematic map, but the low primary production zone was smaller. The Accuracy Index of the Winter 1988–89 NPP10 thematic map was 90 percent by considering the ten modeled sample points. Only point 3 is not well classified; it was the last point sampled, and it appears shifted from the correct class. The Accuracy Index for the 20 sample points was 75 percent. The NPP was overestimated in the west side of the lagoon. The general aspect of the water masses was in agreement with the NPP isolines map, but there are differences in regions extrapolated by the isolines map, e.g., in the outer border of the water lagoon. In these regions the thematic map generated by the correlations is more precise because it is not an extrapolated map.

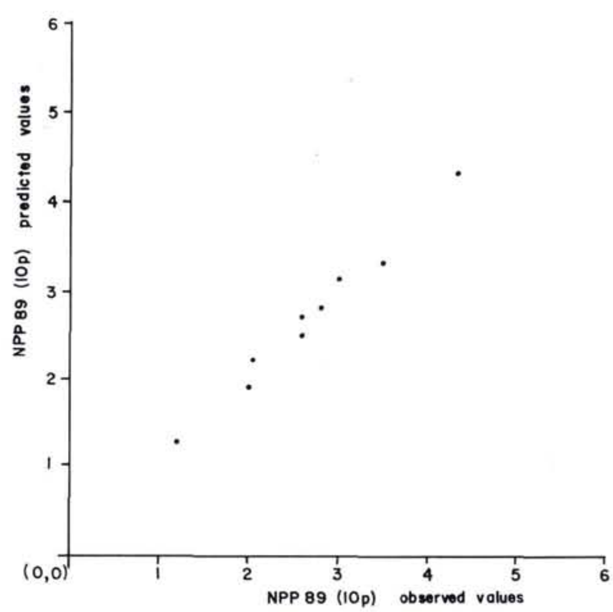

Figure 13. NPP89 (10P) predicted values versus NPP89 (10P) observed values.

Conclusions

In this paper, a methodology for monitoring the surface water net primary production in a small coastal lagoon is proposed. The results are encouraging due to the high Accuracy Indices obtained. However, the implementation of these kinds of studies with "simultaneous" sampling, as well as the acquisition of the Landsat imagery, is difficult. The presence of clouds in the region increased the costs of the project. On the other hand, image processing now available for microcomputers makes the methodology more accessible, lowering the costs of this portion of the project.

The following points must be considered:

- Due to the dynamics of these coastal lagoons, the simultaneity of *in situ* and remote data is considered essential.
- The selection of sample points for modeling is also very important; not only the number, but also the position must be carefully considered.
- The multiband classification with the best simple and multiple regression models has been very functional, increasing the accuracy of the isolated classified models considered in a previous study (Ruiz-Azuara *et al.*, 1989). In the aforementioned paper, the classified thematic maps were representative of the mean values. In the present paper, the zonation is also obtained with a high percentage of accuracy.
- In the case presented, both MSS and TM Landsat images were very useful with high levels of accuracy with respect to the *in situ* data.
- In the Coyuca de Benitez lagoon, the proposed methodology gave good results.
- The advantages and the inherent difficulties of the proposed methodology for monitoring net primary production or any other hydrobiological parameter should be evaluated for each particular case, before being applied in any other water body. During August 1991, the same methodology was applied at two neighboring coastal lagoons: Coyuca de Benitez and Mitla in Guerrero, México. For technical reasons, the "simultaneous" TM Landsat imagery was not available. At present, a simulation of MSS, TM, and SPOT bands within the range 0.3 to 0.9 μm has been developed along with the simultaneous radiometric measurements. Some preliminary results have been reported (Ruiz-Azuara, 1992b).

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