

APPLICATION OF REMOTE SENSING TECHNIQUES TO THE DETERMINATION OF BATHYMETRY IN COASTAL LAGOONS

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Abstract: *The use of remote sensing as a source of information about coastal resources has been extensively explored. At the same time, remote sensing techniques have proven to be an important instrument in the planning, conservation, managing and monitoring of coastal resources. This paper discusses the determination of bathymetry of a coastal lagoon applying remote sensing techniques, using the Conceição Lagoon as a case study. The Conceição Lagoon is a coastal lagoon located at the eastern border of Santa Catarina Island, Brazil, at latitude 27°34' S and longitude 48°27' W. The depths were extracted from a satellite image Landsat 7 ETM+ orbit WRS 220/point 79, acquired on 07/05/2000, calibrated with field data collected in 09/10/2001. The results obtained were compared with bathymetric data of a field survey from 1989. The accuracy of the method is discussed, based on a statistical treatment of the available data. Even though the satellite and field data used for this study were not obtained at the same moment, the method proves reasonable. Suggestions for future research are noted.*

Keywords: Remote Sensing, depth measurements, Lagoa da Conceição, coastal management.

1 Introduction

Coastal lagoons are dynamic and open systems supported by physical energy. They are extremely complex systems in which physical, chemical, biological and geological parameters can change frequently and substantially. For example, the bottom of a lagoon can change over time because of sediment deposits from the surrounding areas. These modifications can be monitored and continuously updated, resulting in new bathymetric maps.

Knowledge and monitoring of the depths of a coastal lagoon depths have a broad application. Studies of water circulation and sediment distribution were conducted by Odebrech and Gomes (1987) and Gré and Horn (1992) in the Conceição Lagoon. Froidefond et al. (1990) found that the interpretation of the spectral response of a water body can also be related to bathymetry. In fact, bathymetric data can be directly applied to the mapping of navigated areas as well as to the updating of nautical charts (Edward and Mumby, 1999).

The use of remote sensing as a source of information about coastal resources, has been extensively explored. This is mainly due mainly to the limitations of conventional techniques for determining spatial and temporal parameters. In addition, remote sensing has proven to be an important instrument in the planning, conservation, managing and monitoring of coastal ecosystems, such as mangroves, coral reefs and lagoons (Edward and Mumby, 1999).

Bathymetry can be estimated through determination of the radiance level per pixel of an

image. Different wavelengths of the visible spectrum penetrate into the water at distinct depths. This occurs mainly because of light attenuation resulting from the interaction of light and water columns (Curran, 1985; Novo et al., 1998). The amount of light that is not absorbed is reflected and registered by satellite sensors (Edward and Mumby, 1999). Therefore, different depths of wavelength penetration, corrected by ground truth, can be related to the bathymetry of the water body. However, there are some limitations with respect to the use of remote sensing for bathymetric studies.

The principal limitation of remote sensing is related to spatial resolution, when the object and processes to be mapped are smaller than the pixel size and therefore cannot be detected. Another limitation has to do with the maximum depth of the electromagnetic radiation (EMR) penetration of the water column. This value depends on the water characteristics of each region. It can be said that the depth of penetration depends on the amount of suspended sediments, phytoplankton concentration and dissolved organic compounds along the water column (Edward and Mumby, 1999).

The utilization of the EMR in the visible spectrum has been the focus of attention of many authors, who have concentrated particularly on the efficiency of the orbital passive sensors in the characterization of shallow marine bottoms. For example, measurement of the blue radiance, the wavelength of maximum penetration of the water column, by the Thematic Mapper (TM) sensor, of the Landsat series, allow the use of orbital images to determine depths (Cabral and Vianna, 1993;

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Benny and Dawson, 1983; Lyzenga, 1978 and Jupp et al., 1988 cited by Edward and Mumby, 1999).

The method employed by Jupp et al. (1988) and described by Edward and Mumby (1999), is one of the methods that offer greater precision in defining bathymetry. It has been applied to clear waters such as the Great Barrier Reef. The question is whether it can be applied or adapted to coastal ecosystems such as a coastal lagoon where the water is not as clear as coral reef waters.

This method is composed of three stages. First, calculation of the depth of penetration zone (DOP zones). Second, an interpolation of the depths in the DOP zones and, third, calibration of the depths of these zones. Each zone indicates a region in which the light is reflected by one band but not by the subsequent band, defining a depth interval. An interpolation is needed since the DOP zones do not determine the depth for each pixel but for an interval of pixels.

This study entails the application of the method of Jupp et al. (1988) in order to determine its viability for bathymetric study of the Conceição Lake, applying remote sensing, with images from the Landsat ETM+ 7 satellite as the main tool.

2 Area of Study

The Conceição Lagoon is located on the eastern border of Santa Catarina Island, just below the Tropic of Capricorn, at latitude 27°34' S and longitude 48°27' W (Figure 1). It extends in a North – South direction, with a total length of 13.5km; a width between 2.5 and 0.15km and a total area of approximately 20km² (MUEHE and GOMES, 1989). It is classified as a lagoon because it is made up of salt water and maintains a permanent communication with the ocean through the Barra da Lagoa channel.

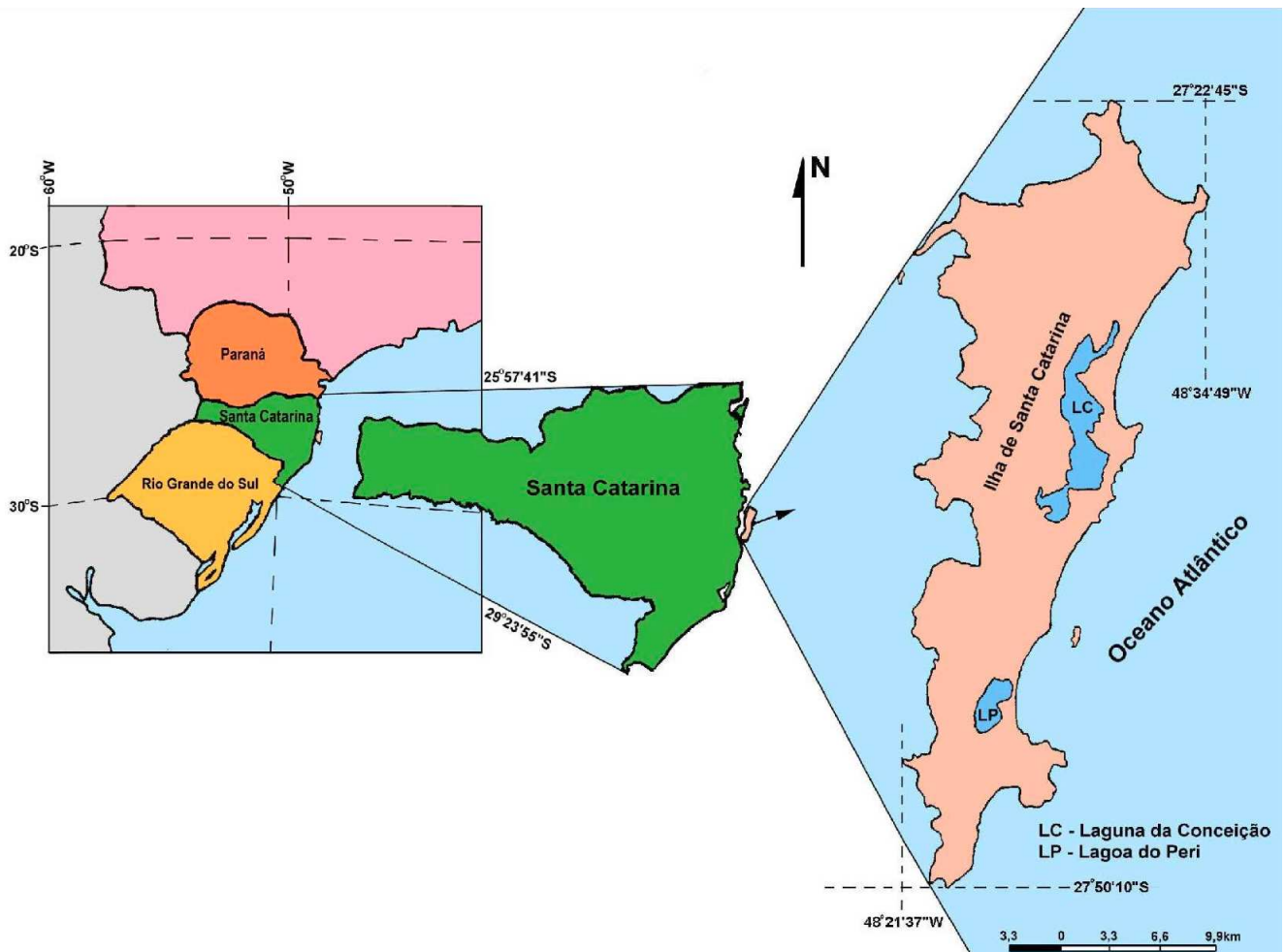


Figure 1 - Location of the Conceição Lagoon, the study area, at latitude 27°34' S and longitude 48°27' W (From Horn, 2006).

Different depths can be found in the study area: the average is roughly 1.7m and the maximum is approximately 8.8m (Muehe and Gomes, 1989). Sand and mud sediments cover

the bottom of the lagoon (Figure 2). The sediment cover is controlled by bathymetry through the action of hydrodynamic agents (tides, currents and waves) and the influence of predominant

winds. The shallowest areas are those with a sandy bottom, while the deepest have silt bottoms. In intermediate depths a mix of sand and mud is observed (Gré and Horn, 1992).

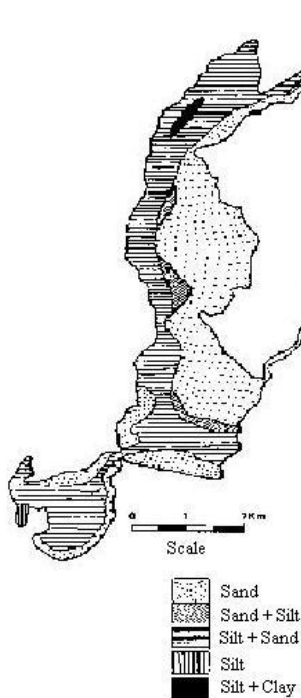


Figure 2 - Sediments distribution at the bottom of the lagoon (from Gré and Horn Filho, 1992).

Odebrecht and Gomes (1987), showed that patterns of dominant winds and evaporation/precipitation are the main factors that determine the circulation and renovation of water. For example, southerly wind conditions, low precipitation and high evaporation favor the input of ocean water to the lagoon. The influence of local topography and input of fresh water is also important to the circulation pattern. In this case, the central area is more stratified, with the water presenting different characteristics at the surface and at the bottom. The northern part of the lagoon presents higher salinity due to the presence of a deep channel that facilitates the circulation from the central area to the northern area.

The lagoon has an average transparency of about 2.35m, since the water column is illuminated the whole year, with a presence of a euphotic zone that extends down to the bottom (Ledo and Sierra, 1993). It is possible to distinguish concentrations of seston, chlorophyll and dissolved oxygen. Under specific conditions of nutrient input, the concentration of seston and pigments tends to increase or to present vertical gradients (Odebrecht and Gomes, 1987). Therefore, the lagoon works as a receptor body and evolves naturally to a state of eutrophication.

The Conceição Lagoon represents an important scenic resource of great ecological, economic and scientific value. It comprises in its

interior different types of habitat that function as breeding grounds and protection for different species; it is a very fragile and complex ecosystem. Throughout the year it is a tourist destination and the site of recreational activities, water sports and fishing. Unfortunately, urban development without proper planning has had a negative impact on water quality, resulting in habitat destruction and sedimentation.

3 Materials and methods

Through a preliminary analysis of a Landsat ETM+ 7 satellite image, a sample area was defined, where 100 samples for depth data were collected. These data were subsequently used to determine the maximum depth of penetration of electromagnetic radiation for bands 1, 2, 3 and 4 of this satellite. In choosing the sample area, bathymetric variation and type of bottom were taken into consideration. The location of each point sampled was determined with a GPS (Ground Position Satellite), model GARMIN 12 XL which presents a resolution or average quadratic error between 15 and 30m.

For the digital processing, an image of the Conceição Lagoon, Landsat ETM+ 7 (orbit WRS 220/point 79) from 07/05/2000 was used. The image was geocoded with SPRING software (Freitas et al, 1996). The oceanography software BILKO 2.0 (Sudarshana et al, 2000) was used for image treatment. Analysis of the sample depths and the statistics was performed by means of mathematical routines.

The DOP zones at Conceição Lagoon were calculated for each one of the Landsat bands: ETM1 (450-520nm), ETM2 (520-600nm), ETM3 (630-690nm) and ETM4 (760-900nm). The pixels that belong to this interval of coordinates form a matrix of 20 columns and 20 lines, forming a total of 40 pixels.

The value of DN for each band is registered and related to the geographic point of the data from the field sample. The deepest and the shallowest pixels are also calculated in order to estimate the maximum depth of penetration of the wavelength considered. Then, a mask is applied for each one of the 4 bands, which results in 4 new images. All pixels located on land are classified as 0 (black) and the one located in the water as 1 (white). The images are then multiplied for each maximum DN defined previously and new resulting images are obtained. A stretch for the resulting images is also applied in order to enhance the contrast and to obtain images with different grey tones. Finally, a color image is produced.

As the calculation of the DOP zones is not a calculation of the depths but the depth interval that corresponds to a pixel interval, an interpolation is carried out for each pixel. Each

type of bottom corresponds to a pixel value (DN) that can vary from a minimum (deep waters) to a maximum (shallow waters – bottom reflection). The interpolation of the depths (Z) can be extracted from:

$$Z = \frac{A_2 - X_2}{2k_2} \quad (\text{Equation 1})$$

Where

Z is depth,

$$X_2 = \log_e (L_2 \text{ DN of the pixel} - L_2 \text{ average})$$

$$K_2 = (X_{2 \text{ maximum}} - X_{2 \text{ minimum}}) / 2 * (z_2 - z_3);$$

$$X_{2 \text{ maximum}} = \log_e (L_2 \text{ maximum} - L_2 \text{ average});$$

$$X_{2 \text{ minimum}} = \log_e (L_2 \text{ minimum} - L_2 \text{ average});$$

$$A_2 = (X_{2 \text{ minimum}} + 2k_2 z_2).$$

Therefore, after defining the constants A, K e L_{average} for each band, the interpolation can be

done, in meters, for each pixel within the DOP zones. For more details see Jupp et al. (1988) and Edward and Mumby (1999).

4 Results and discussion

The choice of the sampling area aims to minimize possible error in the radiance value, especially the one related to the shallow regions. This area represents one of the deepest areas of the lagoon, approximately 6 meters (Muhe and Gomes, 1989). In this same area, the bottom reveals a homogeneous cover, especially sand and silt (Gré and Horn, 1992), besides a high concentration of organic material that shows a darker grey tone.

The physical characteristics of the area are important in determining the maximum and average values of DN. In general, considering as constant the bottom sediment, values for low depths tend to present larger reflectance, which shows that there is an inverse relationship between depth and wavelength of maximum reflectance. Figure 3 shows the DN values for each band of the Landsat and its correspondent depths.

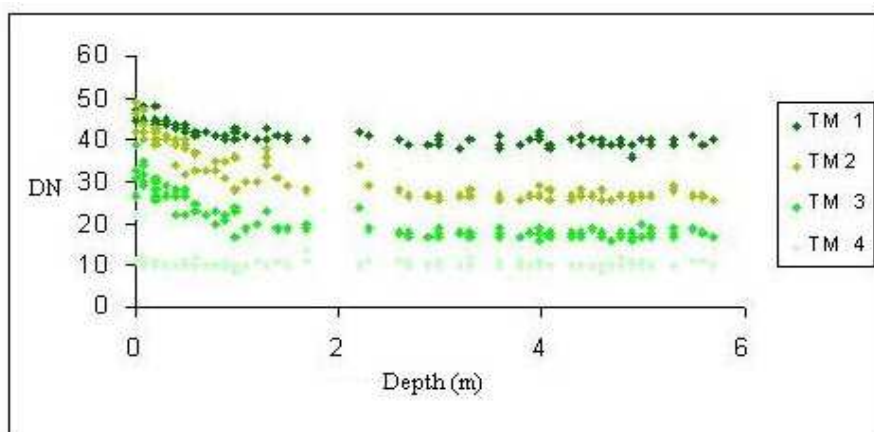


Figure 3 - The relationship between the depth values and DN of Conceição Lagoon for each Landsat ETM+7 band.

The digital number (DN) of deep water was calculated for each band and can be seen in Table 1. With maximum DN calculated for each band it was possible to locate, within the field data, larger DN values than the ones calculated for deep water and its respective depths. Average depth of pixels with DN values larger than the maximum DN and average depth of pixels with DN values smaller or equal to maximum DN for deep waters are calculated for each band. The calculated averages are used to define the DOP zones for each band within the water body. Table 2 shows the depths of the DOP zones of the Conceição Lagoon.

Due to the small sampling number and lack of calibration to atmospheric corrections and suspended material within the water column, the data analyses reveal some DN values out of the pattern. These pixel values are probably influenced by bottom or suspended material reflectance and were excluded from the calculations.

It is important to establish the relationship between the DN values of the Conceição Lagoon and the penetration zones. This is done through a definition of conditions determined with the help of tables 1 and 2. These conditions are presented in Table 3. If any of these conditions are not true or the pixel shows a larger value in one band than in

the subsequent bands, then this pixel is recorded as zero and not mapped, being filtered out of the

final image.

Table 1 - Values of DN for deep water pixels.

	Landsat TM Bands			
	1	2	3	4
Maximum DN for deep water ($L_{\max \text{ depth}}$)	40	27	19	11
Average DN for deep water ($L_{\text{aver depth}}$)	38.85	26.4	17.6	10.47
Minimum DN for deep water ($L_{\min \text{ depth}}$)	37	26	16	9

Table 2 - Maximum depth of penetration (z) in meters, for each band.

Depth in meters	Landsat ETM+ Bands			
	1	2	3	4
Depth of the deepest pixel with $DN > L_{\max \text{ depth}}$	5.575	4.3675	2.5675	1.775
Depth of the shallowest pixel with $DN \leq L_{\max \text{ depth}}$	2.9675	2.775	1.4675	0.075
Average depth of pixels with DN values $> L_{\max \text{ depth}}$	4.1575	4.0175	1.6960	1.225
Average depth of pixels with DN values $= L_{\max \text{ depth}}$	4.5445	4.3260	2.8275	1.7572
Estimated maximum depth of penetration (z) = average of DN values $\leq L_{\max \text{ depth}}$ and DN values $> L_{\max \text{ depth}}$	4.3510	4.1717	2.2617	1.4911

Table 3 - Conditions for providing signature pixels of depth of penetration zones.

Landsat ETM+ Bands	1	2	3	4	DOP Zones
Maximum DN for deep water	48	27	19	11	
If pixel DN	≤ 40	≤ 27	≤ 19	≤ 11	Depth $> 4.35\text{m}$
If pixel DN	> 40	≤ 27	≤ 19	≤ 11	Depth 4.17 – 4.35m (zone 1)
If pixel DN	> 40	> 27	≤ 19	≤ 11	Depth 2.26 – 4.17m (zone 2)
If pixel DN	> 40	> 27	> 19	≤ 11	Depth 1.49 – 2.26m (zone 3)
If pixel DN	> 40	> 27	> 19	> 11	Depth 0 – 1.49m (zone 4)

The application of these conditions, together with mathematical operation between the bands and the mask of the band 4, results in the DOP masks (Figure 4). Each one of these images registers the depth interval in their respective bands. Band 1, for example, penetrates deeper and as a consequence, can

sample the deeper areas, especially the ones at the centre and western edge of the lagoon. On the other hand, band 4 hardly penetrates into the water body, being restricted to the eastern edge of the lagoon where the shallowest depths are found.

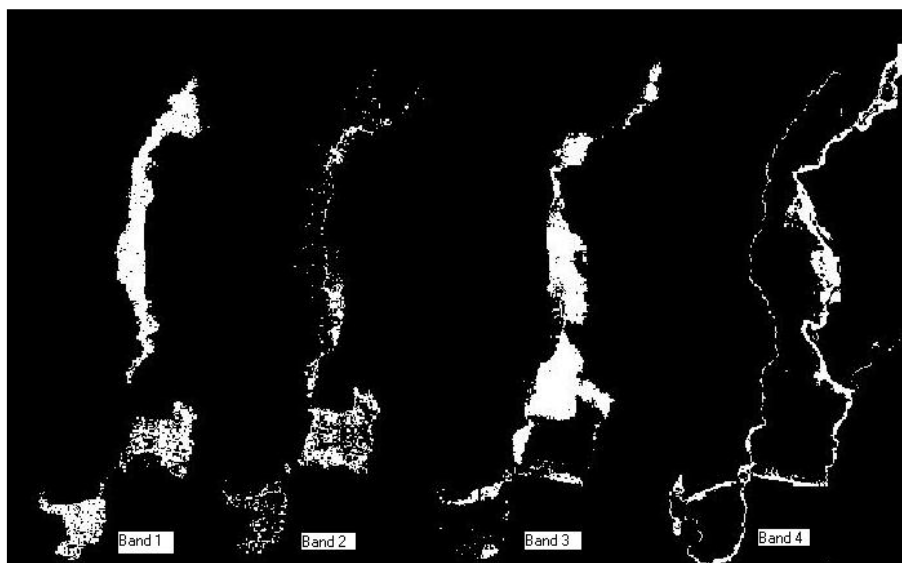


Figure 4 - DOP masks for each depth interval from each satellite band.

One image is created from grouping the DOP zones (bands 1, 2, 3 and 4). This image shows the depth intervals in scales of grey and can be seen in Figure 5a. The color composition of the DOP zones in one image allows a better visualization of the behavior of the spectral bands in relation to the depths. This relationship can be observed in Figure 5b. In this Figure, band 1 represents areas of deeper penetration, in an

interval larger than 4.17m, in blue. Band 2, which in many situations overlaps band 1, reaches an area with a depth interval smaller than the previous band, a value between 2.26 and 4.17m, represented by the green color. Band 3 shows a depth interval between 1.49 and 2.26m, and is represented by the red color in the Figure. Band 4, is located at the surface in an interval from 0 to 1.49m; it is in yellow.

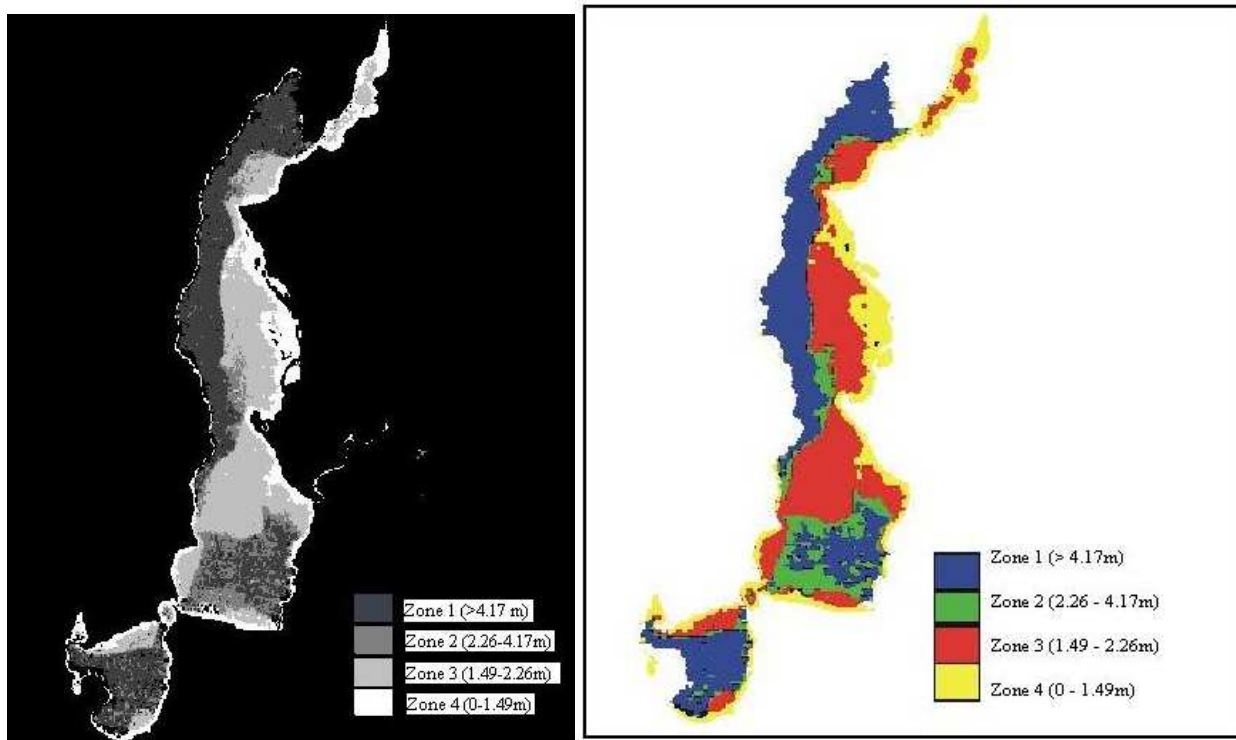


Figure 5 - (a) Composition of Figure 5 showing the depth intervals in scales of grey. Scale is 1:50000. (b) Colour composition of the depth intervals. Scale is 1:50000.

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The constants A and K (equation 1) for each band are calculated from the determination of the intervals of the DOP zones. In order to calculate the K constants, it is necessary to find the maximum and minimum DNs. These values are obtained from the histograms generated from

the product between each band and its respective DOP mask. The histograms ensure that only pixels from a defined DOP zone are being analyzed, avoiding overlap of bands. The DN values and constants are shown in Table 4.

Table 4 - Maximum and minimum DN values obtained from histograms of Landsat images and the values of K and A constants, obtained from previous Equations.

	TM band 1	TM band 2	TM band 3	TM band 4
DOP 1 (Maximum and minimum DN)	45 -54			
DOP 2 (Maximum and minimum DN)		29 - 38		
DOP 3 (Maximum and minimum DN)			20 - 37	
DOP 4 (Maximum and minimum DN)				12 - 34
K	2.5140	0.3914	1.3559	0.9174
A	23.6939	4.2218	7.0090	3.1580

Figure 6a shows the interpolated depths through seven different intervals. The interpolation is done between depth intervals. Deeper areas are shown as darker blue and shallow regions as light blue, according to the scales of grey obtained from the DOP zones. In order to compare the interpolated depths with field data, the interpolated image from the satellite is superimposed on a bathymetric map of Conceição

Lagoon (Figure 6b) from 1989. The interpolation obtained through the satellite is based on 100 field bathymetric data. The satellite image and the 100 data were not acquired on the same day. The satellite image is from 07/05/2000 and the field data from 09/10/2001. Figure 6 shows that the depth contours of the interpolated image are very close to the bathymetric lines from the field.

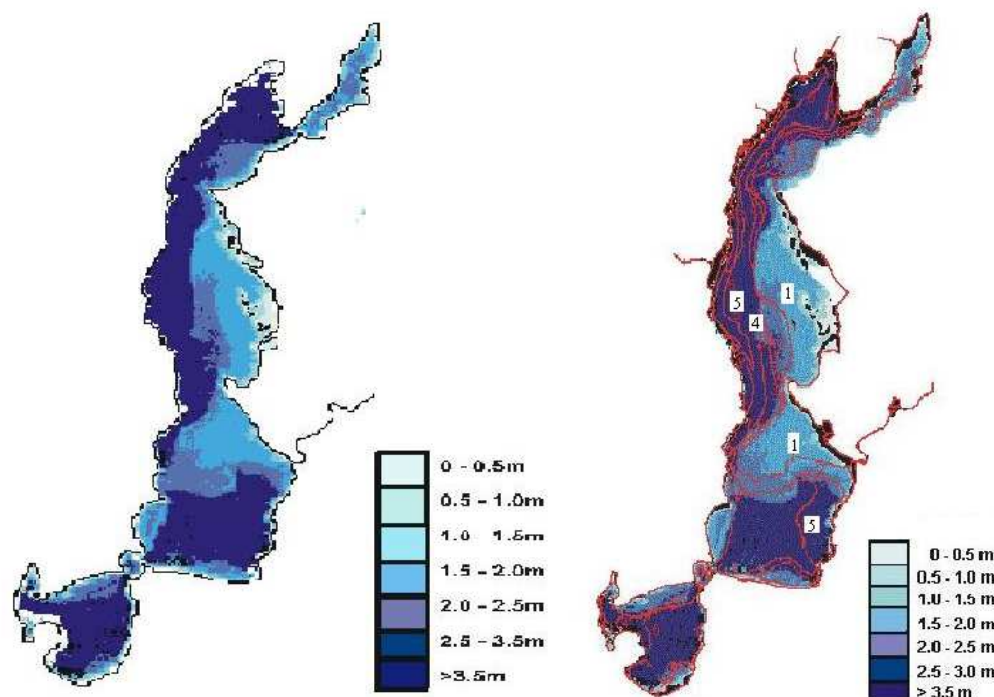


Figure 6 - (a) Interpolated depths through seven different intervals. (b) The overlay between the interpolated image and a bathymetric map of Conceição Lagoon.

The visual comparison can provide only an idea of the similarities between the two maps. However, this kind of comparison does not demonstrate the accuracy of the method. In order to determine the accuracy of the method, a correlation between the field data and predicted data must be performed. The resulting correlation is 0.87, which means that 87% of the field data can be explained by the predicted data from the

method (Figure 7). It should be noted that due to the conditions in which the method was conducted, it would be risky to affirm that the bathymetric map from the satellite can, for example, be used for navigation purposes. Besides the standard deviation of ± 0.6 , the average differences between the predicted and observed data, approximately 1.06m, are much too high to apply to nautical charts.

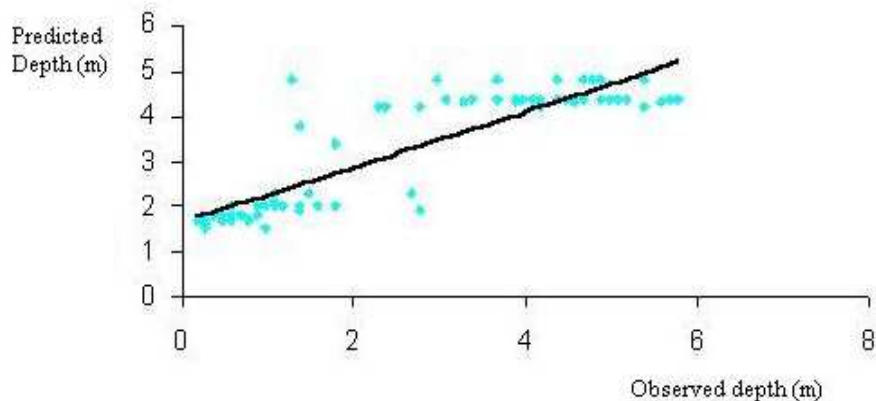


Figure 7 - Correlation between the field data and predicted data.

5 Conclusion

The application of remote sensing techniques in the bathymetric study of coastal ecosystems has been the subject of considerable attention in recent years. Based on the degree of accuracy, the results obtained here cannot yet be considered very reliable, but the method does show real potential for future application. In the particular case of the Conceição Lagoon, the images generated for the DOP zones and bathymetry show a great resemblance when compared to previous studies using conventional methods.

The kind of methodology available for these types of studies is, in general, developed for large-scale marine coastal areas with correspondingly larger depths intervals. In the case of coastal lagoons such as the Conceição Lagoon, the methodology developed by JUPPE *et al.* (1988) has been quite satisfactory, albeit with some limitations. These limitations pertain mainly to the amount of collected data, simultaneity with the satellite passage and calibration with the suspended material. Other factors that could also affect the spectral response are the atmosphere and type of substrate.

The wind, for example, can transfer bottom material to the water column. These increases in suspended material directly influence the spectral response. In the Conceição Lagoon, the south wind (more intense) and the northeast

wind (more frequent) can be of great significance in the evaluation of image radiance levels and should be taken into account in the adjustment of DNs of the pixels sampled.

Bathymetric charts are of great value especially in regard to navigation, definition of research areas and choosing locations for marina development, as well as monitoring and management. Bathymetric data from Conceição Lagoon obtained by satellite, although they reflect the depths fairly accurately, do not offer sufficient cartographic precision to be used as nautical charts. However they do provide enough information for other studies that do not require a high level of precision, for example, habitat mapping, dispersion and deposition of sediments.

The results of this study indicate the need for more research, related principally to radiometric calibration, such as studies of the calibration of the model related to suspended material, atmospheric influence and bottom characteristics. Acquiring field data simultaneously with the satellite overpasses could also minimize radiometric problems within the obtained and predicted data from the model.

The utilization of the Landsat 7 ETM+ satellite in bathymetric studies, apart from its middle spatial and temporal resolution, offers greater efficiency due to the number of bands and good penetration into the water, all at a reasonable cost to governmental and research institutions in developing countries.

6 Aplicação de técnicas de sensoriamento remoto para a realização de levantamento batimétrico em lagoas costeiras

Resumo: O uso de sensoriamento remoto como fonte de informação para estudos dos recursos costeiros tem sido amplamente explorado. Técnicas de sensoriamento remoto têm-se mostrado como uma importante ferramenta no planejamento, conservação, gerenciamento e monitoramento de recursos costeiros. Este trabalho discute a determinação da batimetria de uma lagoa costeira através da aplicação de técnicas de sensoriamento remoto, usando a Lagoa da Conceição como caso de estudo. A Lagoa da Conceição representa uma lagoa costeira localizada na margem leste da Ilha de Santa Catarina, Brasil, nas latitudes 27°34' S e longitude 48°27' O. As profundidades são extraídas de uma imagem do satélite Landsat 7 ETM+ orbita WRS 220/79, adquirida em 07/05/2000, calibrada com dados de campo coletados em 09/10/2001. Os resultados obtidos são comparados com dados batimétricos de um levantamento de campo realizado em 1989. A precisão do método é discutida, com base no tratamento estatístico dos dados disponíveis. Apesar de os dados do satélite e do campo, para este estudo, não terem sido obtidos em um mesmo momento, o método se apresenta razoável. Sugestões para futuras pesquisas são apresentadas.

Palavras-Chave: Sensoriamento Remoto. Levantamento batimétrico. Lagoa da Conceição. Gerenciamento costeiro.

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