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STUDY OF THE TEMPORAL DYNAMICS OF THE SURFACE OF A LAGOON ON THE NORTH COAST OF RIO GRANDE DO SUL, USING REMOTE SENSING

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Abstract: The Jacaré Lagoon (-29º33'S; -49º81'W // 29°19'48"S and 49°48'39"W), located in a priority area for conservation in the municipality of Torres-RS, is surrounded by a rich mosaic of ecosystems. However, it is under pressure from anthropogenic activities, especially rice farming through surface irrigation and urbanization. The aim of this study was to contribute to the State Environmental Agency's inspection activities in relation to a complaint about a reduction in the area of this lagoon's water mirror, allegedly caused by irregular and excessive water withdrawals. As the variations in the water mirror of the Jacaré Lagoon are little known, we sought to subsidize the investigation by studying the space-time dynamics of its flood surface and the main causes of the variation. Following the characterization of the rainfall regime and normal evapotranspiration in the region, 20 Landsat 5 satellite images and one Landsat 8 image were selected from the months of rice cultivation between 1985 and 2014. In these images, the lagoon's flooded areas were delimited and quantified using the SPRING 4.3.3 application. Comparisons between the variations in the size of the flooded areas and the climate data did not show a significant decrease in the water mirror in the historical series. The results indicate that the dynamics of the surface area of Jacaré Lagoon occurred within the expected seasonal variations, not allowing the assumptions raised in the investigated process to be evidenced. It is also recommended that, among other parameters, more refined remote sensing techniques be used to examine the temporal variation in the coverage of aquatic macrophytes, whose growth towards the interior of the lagoon masks the real size of the lagoon's surface area.

Keywords: Jacaré Lagoon, geoprocessing, rainfall, investigation, temporal variation, lagoon area, pluviometric precipitation

INTRODUCTION

The entire length of the Coastal Plain of Rio Grande do Sul is home to a collar of lagoons, lakes and wetlands formed from the movement of marine sediments during the glaciations of the Quaternary Period. In this region, there is a mosaic of highly diverse aquatic and terrestrial ecosystems, justifying its classification by the Ministry of the Environment as an area of high or very high ecological importance and a priority for conservation (BRASIL, 2007). Throughout the year, these lagoons can show variations in the surface area of the water mirror (DOMINGUES *et al.*, 2015). This is because they are generally shallow bodies of water and are therefore vulnerable to fluctuations in the water regime (SCHÄFER *et al.*, 2009).

The water mirror of these lagoons can undergo changes in diameter over the years. This dynamic can be caused by natural events, such as fluctuations in the water regime, the tidal regime and the natural and longer process of clogging and ageing of the lagoon (SCHÄFER *et al.*, 2009). In a previous study on the Jacaré Lagoon, it was found that its floodplain surface may be subject to natural variations dependent on seasonal changes in the water regime (MIRANDA *et al.*, 2014).

Artificial factors imposed by anthropogenic action can also influence variations in the surface area of these lagoons, such as sand dredging, the withdrawal of water for irrigation, the damming and detour of rivers, and the acceleration of natural processes such as artificial eutrophication and the silting up of the lagoon (SANTOS, 2000). The use of water, when not planned and organized, can generate conflicts between water users and also cause negative impacts on ecosystems

A complaint about alleged clandestine water withdrawals and a reduction in the area of the Jacaré Lagoon, Torres, RS, was forwarded to the State Environmental Agency - the

Henrique Luis Roessler State Foundation for Environmental Protection (FEPAM), and to the local Basin Committee - the Mampituba River Basin Management Committee. The complaint alleged that the Jacaré Lagoon was drying up due to excessive use of the water through clandestine draining and dredging of sand from the banks. As a result, *on-site* inspections and meetings on the issue were held by the competent bodies. However, these actions have not produced any physical evidence or conclusions about the allegation that the lagoon area has been compromised.

In an attempt to support this research, aim of this study was to investigate the spatio-temporal variation in the flood surface of Jacaré Lagoon and the natural and artificial factors that interfere with the lagoon's water flow. As well as contributing to knowledge of the temporal dynamics of Jacaré Lagoon, the information gathered could be useful in the future resolution of other conflicts related to the use of water in the Mampituba river basin.

MATERIAL AND METHODS

STUDY AREA

Lagoa do Jacaré is located between the coordinates 29°19'48"S and 49°48'39"W, in the municipality of Torres, in the North Coast region of the Coastal Plain of Rio Grande do Sul, where it is part of the Mampituba L-50 River Basin. It is located in a floodplain seven kilometers from the coast and about 12 kilometers from the first elevations of the Serra Geral. According to Santos (2000), the Jacaré Lagoon is not a closed system, as its waters flow into the Monteiro River, which later connects to the lower stretch of the Mampituba River (Figure 1). Located to the west of the Jacaré Lagoon, in the same hydrographic basin, and upstream of the Monteiro River, is the Morro do Forno Lagoon, which through this river could exchange waters with the Jacaré Lagoon, depending on local water conditions. During high tide and the flooding of the Mampituba River, water can flow in the opposite direction, with water from these rivers entering the Jacaré Lagoon (SANTOS, 2000).

Belonging to the Atlantic Forest Biome, the surrounding region is characterized by the existence of marshes, vegetation from remnants of the Dense Ombrophilous Forest, Pioneer Formations and fields altered by agricultural activities, such as the cultivation of bananas, corn, horticulture and, predominantly, the cultivation of irrigated rice - the activity responsible for the greatest use of water in this lagoon (SANTOS, 2000). Due to its biodiversity and location, the conservation of the region has been recommended as part of the proposed Ecological Microcorridors of the Itapeva State Park (KROB; KINDEL; BOHRER, 2010).

As for the soils, from east to west there is a transition between hydromorphic quartzarenic neosol and eutrophic melanic gleissolo, with indications of organosols in the lagoon area (STRECK et. al. 2002). The regional climate is Cfa, according to the Köppen classification (1948), humid subtropical with no dry season and hot summers. The average annual temperature recorded by the Torres Meteorological Station is 18.9°C, with February being the warmest month, with an average of 23.3°C, and July the coldest month, with an average temperature of 11.3°C. The annual temperature range is moderate due to the influence of the ocean, the winds blow predominantly from the northeast quadrant and throughout the year, being more intense during the spring and summer months (TOMAZELLI, 1993).

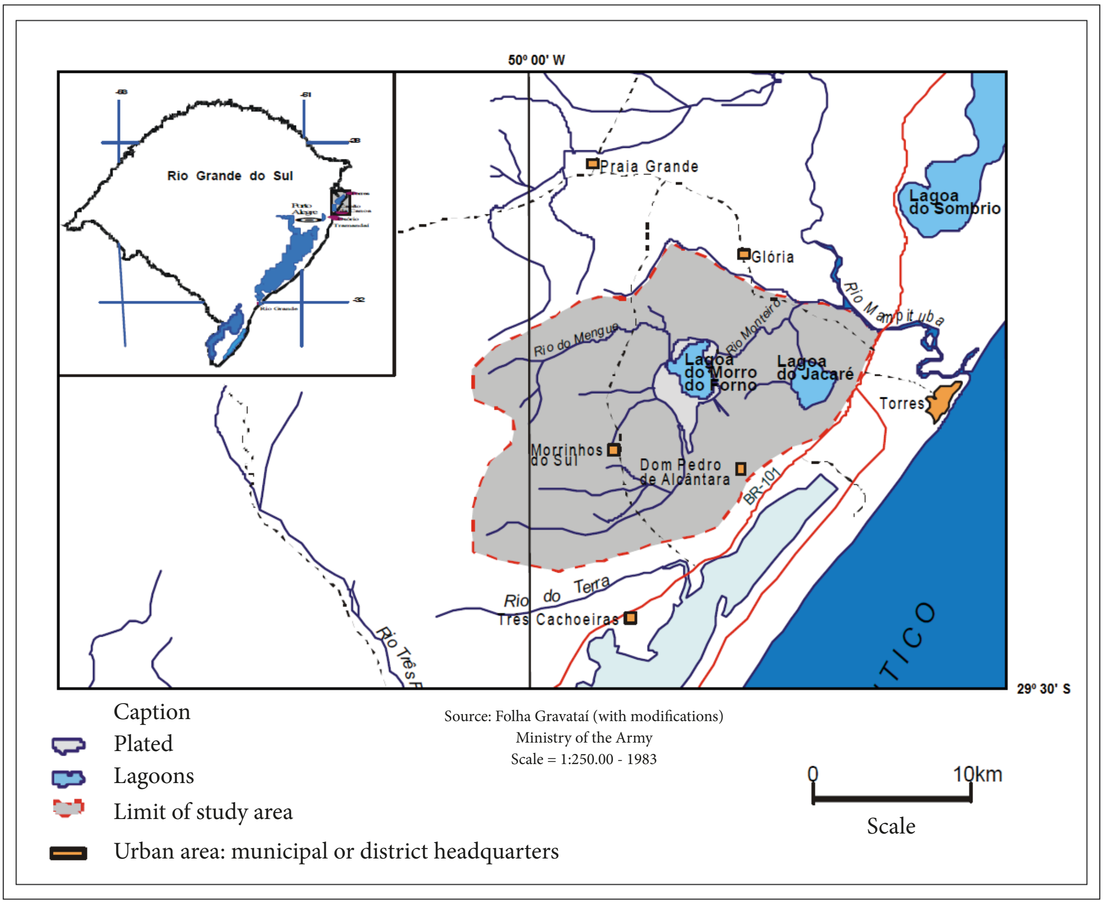

Figure 1. General location map of the study area, municipality of Torres, RS. Source: Adapted from Santos (2000).

RAINFALL AND EVAPOTRANSPIRATION (ETP)

The monthly accumulations of rainfall were determined and the monthly potential evapotranspiration for each year was calculated for the period from 1985 to 2014, with the exception of 1986, 1987, 1990 and 2001, when no data was available. The monthly averages for the period were determined. The Thornthwaite (1948) method was used to calculate the monthly ETP for each year of the historical series. Rainfall, maximum, average and minimum temperature data was obtained from the Torres Meteorological Station of the 8th Meteorological District of the National Meteorological Institute (8ºDISME/INMET), located about 7 km east of Jacaré Lagoon. Based on this data, the lagoon's water conditions were characterized in the months referring to the dates of the satellite images used in the study, considering monthly rainfall as the water inflow and monthly potential evapotranspiration as the lagoon's water outflow.

GEOPROCESSING SATELLITE IMAGES

The floodplain of the Jacaré Lagoon was delimited using satellite images covering the period between 1985 and 2014. Of these, 20 images from the Landsat 5 Thematic Mapper (TM) satellite were used, obtained from the online catalog of the National Institute for Space Research - INPE, and one image from the Landsat 8 satellite with the OLI and TIRS (Thermal Infrared Sensor) sensors, from the Earth Explorer catalog of the United States Geological Survey (USGA).

The images were always selected between November and April, to coincide with the irrigated rice growing season in the region (STEINMETZ and BRAGA, 2001). To geoprocess the images, a database was created in the SPRING 4.3.3 software, where the images were inserted and georeferenced, using a GeoCover Landsat 7 image from May 7, 2000, from the Global Land Cover Facility image catalog developed by the University of Maryland (USA) as a basis for obtaining support points. Georeferencing used 27 homologous support points, the Universal Transverse Mercator (UTM) projection system, the Regional Geodetic System for South America - South American Datum SAD69, a polynomial of degree 2, nearest neighbor interpolation and an average squared error of less than one pixel.

The delimitation of the Jacaré Lagoon area was done by manually vectorizing each image, using the composition of bands 543 in the RGB channels in the Landsat 5 images and the composition of bands 654 in the RGB channels Landsat 8 satellite images. In both types of images, the composition of the bands corresponds to the mid-infrared, near-infrared and red. The areas corresponding to the marsh surface in each image were calculated by adding up the number of pixels inside the delimited area, using the "metric operations" tool in the SPRING 4.3.3 software.

FIELD RECONNAISSANCE

Visits were made on March 7 and July 24, 2013 to visually check the area of the Jacaré Lagoon, the characteristics of the vegetation and land use in its surroundings.

RESULTS AND DISCUSSION

The rainfall regime in the Lagoa do Jacaré region is characterized by two rainy periods: one in summer, covering the months of January, February and March, and the other at the end of winter, including part of spring, with the months of August, September and October (Figure 2). Rainfall in the summer rainy season is higher (between 148 and 174 mm) than in the winter (between 123 and 149 mm). However, evapotranspiration loss is higher in the summer period, where average monthly ETP values vary between 110 and 127 mm. In the rainy season, between the end of winter and spring, evapotranspiration loss is lower, with average monthly ETP values ranging from 42 to 74 mm.

Table 1 shows that the accumulated rainfall values, representative of the dates of the images, ranged from 40.2 mm (30/01/1985) to 319.4 mm (20/01/1993). Potential evapotranspiration values ranged from 53.13 mm. $month^{-1}$ (16/12/2014) to 138.01 $mm.month^{-1}$ (04/02/2010).

Analysis of the images (Figure 3) showed that the largest areas of flooding in the lagoon occurred on the following dates: 30/01/1985 (312.74 ha), 07/01/1988 (403.75 ha), 26/02/1989 (299.99 ha) and 31/01/1991 (311.83 ha). The smallest areas of flooding were obtained on 07/03/2004 (227.49 ha), 26/03/2005 (256.51 ha), 04/02/2010 (254.61 ha) and 16/12/2014 (259.80 ha). The average of the largest areas was 332.0 ha and of the smallest areas was 249.5 ha, both values remaining close to the total average of 284.2 ha of data from the historical series of images, with a standard deviation of 33.7.

Table 1 also shows that the highest visible flooded area values found for Jacaré Lagoon do not coincide with the El Niño period and the period of greatest water availability in the region (highest P-ETP values), as well as the highest accumulated rainfall values. The same is true for the lowest flooded area values,

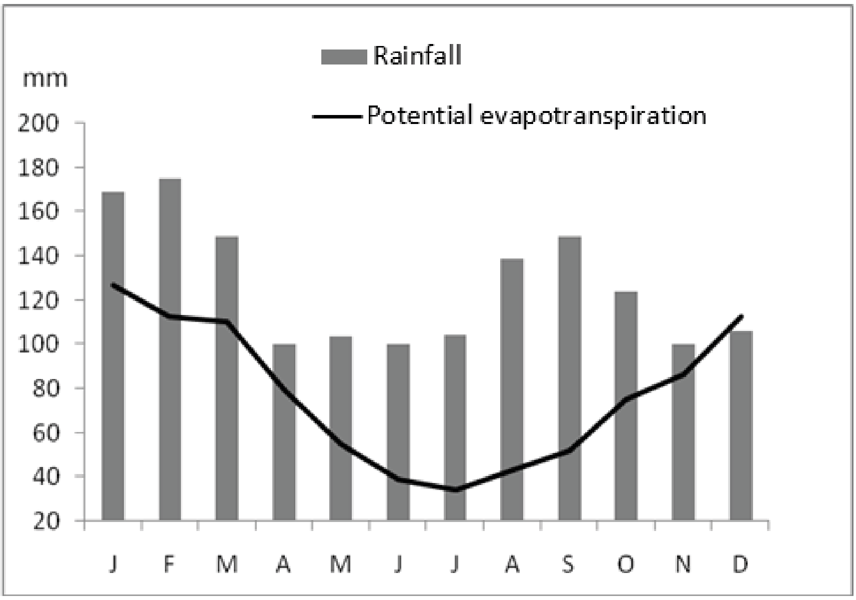

Figure 2. Normal monthly precipitation and evapotranspiration in the Lagoa do Jacaré region, Torres, RS.

Date of images	P (mm)	ETP (mm.month^{-1})	P-ETP (mm)	Area (ha)	Climate anomalies
L5 30/01/1985	40.2	111.87	-71.67	312.74	LN Weak
L5 07/01/1988	248.8	132.7	116.1	403.75	LN Strong
L5 26/02/1989	52.4	112.57	-60.17	299.99	LN Strong
L5 31/01/1991	149.8	111.97	37.83	311.83	EN Strong
L5 19/02/1992	116.0	106.98	9.02	277.07	EN Strong
L5 20/01/1993	319.4	124.40	195.0	289.92	EN Strong
L5 25/12/1994	137.7	13.,37	6.33	295.23	EN Moderate
L5 16/04/1995	82.5	84.05	-1.55	282.44	EN Moderate
L5 30/12/1996	70.9	121.75	-50.85	275.70	LN Weak
L5 16/02/1997	112.7	110.95	1.75	283.09	EL Strong
L5 21/01/1999	70.4	135.13	-64.73	279.21	LN Moderate
L5 09/02/2000	247.8	131.78	116.02	280.06	LN Moderate
L5 07/03/2004	91.8	106.07	-14.27	227.49	EN Weak
L5 26/03/2005	222.6	109.07	113.53	256.51	EN Weak
L5 24/11/2006	189.2	83.70	105.50	279.10	EN Weak
L5 28/02/2007	192.0	109.11	82.89	273.74	LN Strong
L5 03/04/2008	87.1	103.50	-16.4	278.87	LN Strong
L5 02/12/2009	149.1	109.86	39.24	282.49	EN Weak
L5 04/02/2010	164.9	138.01	26.89	254.61	EN Weak
L5 06/11/2011	77.6	75.00	2.60	265.74	LN Strong
L8 16/12/2014	94.5	53.13	41.37	259.80	EN Moderate
Average	138.9	109.70	29.30	282.80	-
Maximum	319.4	138.01	195.0	403.75	-
Minimum	40.2	53.13	-71,60	227.49	-
Standard Deviation	74.6	21.3	70.50	33.7	-

Table 1. Accumulated rainfall data representative of the date of the image (P), potential evapotranspiration representative of the date of the image (ETP), area corresponding to the floodplain of the Jacaré Lagoon and occurrence of climatic anomalies, El Niño (EN) and La Niña (LN). L5 - Landsat 5; L8 - Landsat 8.

where it is not possible to find a significant relationship between the periods of La Niña occurrence, the period of lowest water availability (lowest P-ETP values) and also with the highest evapotranspiration values and lowest accumulated rainfall.

One explanation for these observations could be the presence, on the perimeter of the Jacaré Lagoon, of a variable cover of aquatic macrophyte plants which, being quite large in some places, may it make impossible to clearly distinguish between the dry edge of the lagoon and the start of this vegetation cover in the flooded area, masking the real area of the lagoon in the manual vectorization process of the images. A growing proliferation of macrophytes in the flooded area, starting from the edges of the lagoon, can give the impression that the body of water is shrinking.

Figure 3 shows the situation of the wetland area found during the field trip carried out in the summer (07/03/2013). Figure 3A shows the southern face of the Jacaré Lagoon from a viewpoint located on the BR 101 highway. Figures 3B and 3D were taken at access points closer to the shore, showing the macrophyte plants growing on the northeast side of the lagoon, in the permanent preservation area (APP). Figure 3C shows the cultivation of irrigated rice around the lagoon.

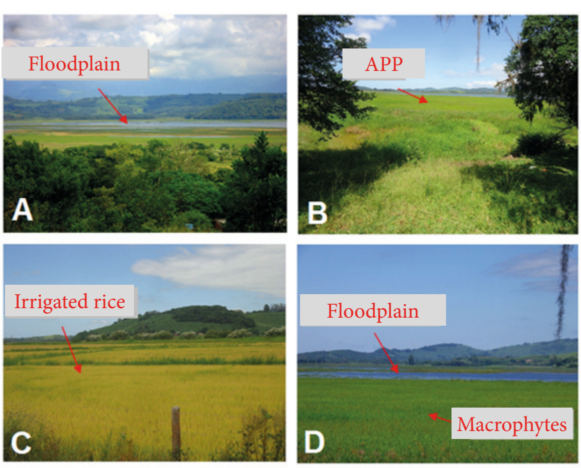

Figure 3 - Views of the shores and plant covers in the vicinity of the Jacaré Lagoon, Torres-RS.

Visual analysis of the 22 satellite images from the historical series from 1985 to 2014 (Figures 4, 5 and 6) shows the area of the water mirror over the years. There was also a gradual increase in the macrophyte population on the southern side of the lagoon (the lower portion in the images), correlating with the occurrence of the largest areas of the water mirror visible the images processed in the early years (1985, 1988, 1989 and 1991) and the smallest visible areas in the later years of the historical series (2004, 2005, 2010 and 2014).

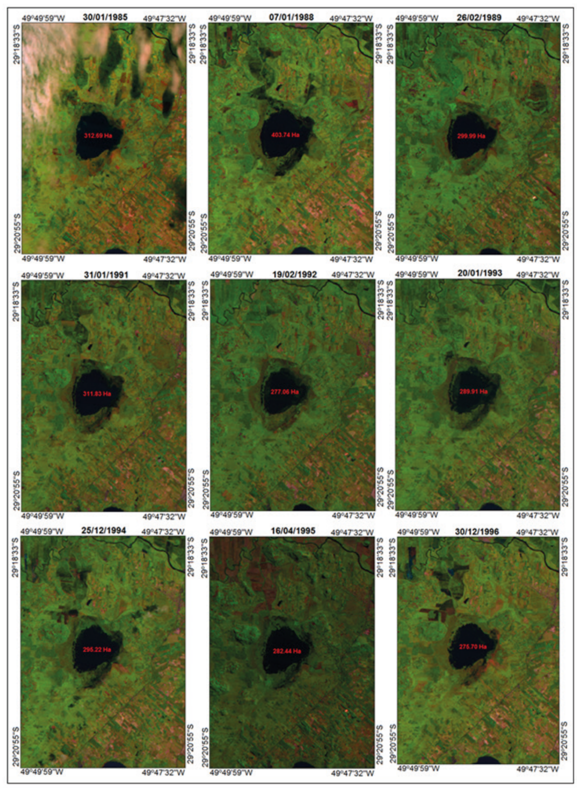

Figure 4 - Satellite images of the Jacaré Lagoon in 1985, 1988, 1989, 1991, 1982, 1993, 1994 and 1996, and the respective area of the water mirror calculated in hectares.

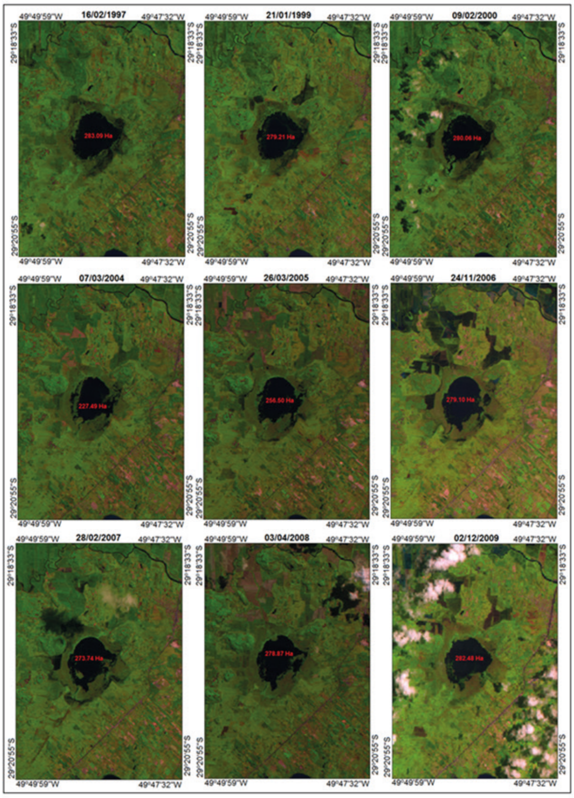

Figure 5 - Satellite images of the Jacaré Lagoon in 1997, 1999, 2000, 2004, 2005, 2006, 2007, 2008 and 2009, and the respective area of the water mirror calculated in hectares.

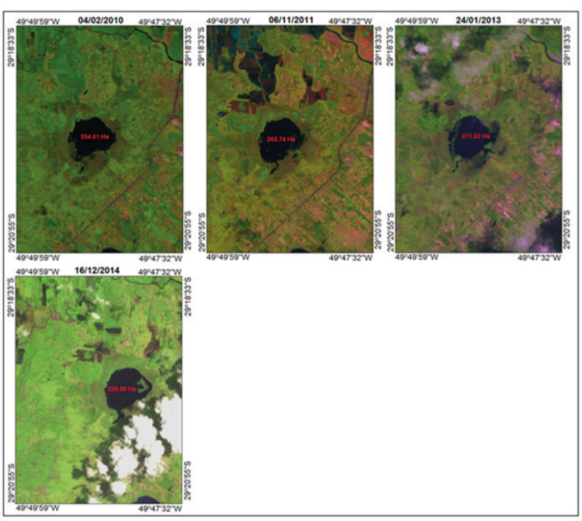

Figure 6 - Satellite images of the Jacaré Lagoon in 2010, 2011, 2013 and 2014, with the respective area of the water mirror calculated in hectares.

According to Noemberg *et. al.* (1999, *apud* Miranda and Costa, 2015), aquatic macrophyte plants are of great importance to the ecosystem, but their proliferation, due to the eutrophication of the aquatic environment, is rapid, resulting in problems such as the obstruction of water flow, making navigation difficult, reduced fishing due to the amount of biomass and a drop in oxygen. Miranda and Costa (2015) also point out that, due to these problems, data generated by special remote sensing techniques can be important tools for accurately obtaining the areas affected by aquatic plants and their development over time.

According to Mesquita *et al.* (2013), the development macrophytes in water bodies can indicate, for example, the occurrence of untreated sewage and drainage from agricultural areas. These authors, as well as Galo *et al.* (2002), used remote sensing techniques, with multispectral orbital images, which made it possible to quantify and map, over time, the dispersion of macrophytes in dams and reservoirs.

CONCLUSIONS

In this study, by analyzing a historical series of Landsat images over 29 years, it was possible to calculate the visible area of the water mirror of Jacaré Lagoon and verify its temporal variation. Comparisons of the calculated areas with climatic data from the region, during the historical series studied, did not show a significant decrease in the water mirror in the historical series and demonstrated that there was no direct correlation between the areas and periods of greater or lesser water availability due to precipitation, potential evapotranspiration and El Niño or La Niña anomalies (Table 1). These results indicate other factors responsible for the dynamics of the area visible with water in the Jacaré Lagoon. Satellite images and on-site observations point to the development of macrophytes in the interior of the lagoon and a temporal variation in the size of this vegetation cover.

After analyzing these results, it was found that the geoprocessing techniques currently applied to the Landsat 5 and 8 images were unable to detect the real size of the Lagoa do Jacaré's floodplain, as the high quantity of macrophytes and their variation made it difficult to see the limits of the lagoon's floodplain. This made it impossible to draw consistent conclusions about the decline of the lagoon caused by irregular drainage of its water, inferred in the complaint, and the natural and artificial causes that affect its dynamics. However, the images (Figures 4, 5 and 6) show that the areas of the water mirror have not varied significantly in recent years. The results indicate that the dynamics of the surface area of Jacaré Lagoon occurred within the expected seasonal variations, not allowing the assumptions raised by the complaint to be evidenced in the process investigated.

Although the geoprocessing techniques used did not enable a clear distinction to be made between the dry edge of the lagoon and the beginning and end of the macrophyte cover, which masks the real area of the lagoon, this work could serve as a basis for future studies that apply geoprocessing techniques that enable distinction to be made and also those areas covered with macrophytes to be counted as wetlands. Thus, for a more precise investigation into the possible decline of the lagoon, caused by anthropogenic impacts such as clandestine water drainage, sewage and agricultural inputs, it is suggested that the remote sensing methodology applied be refined to enable the mapping and monitoring of aquatic vegetation on the perimeter of the Jacaré Lagoon

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