INFERRING FLUCTUATIONS OF THE AQUIFER BY MONITORING THE AREA OF SMALL LAKES IN A BRAZILIAN SAVANNA REGION USING A TEMPORAL SEQUENCE OF 50 LANDSAT IMAGES

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ABSTRACT:

Water availability is subjected to a complex dynamic involving fluctuation of the aquifer level, itself subject to climatic and edaphic factors as well as land use and land cover. Human pressure can have a drastic effect on the aquifer level, the effect of which are often only noticeable after years of continuous usage. In this article we are using a temporal sequence of 50 Landsat images to study a complex of small lakes in Northern Minas Gerais. Our objective is to quantify the fluctuations of the aquifer for the 1984-2009 period by monitoring the area of these lakes bi-yearly and compare it with the hydric balance to understand its evolution. Having no measurements of the aquifer, we developed a methodology entirely based on remote sensing and meteorological data. Because these lakes are very small, the 30 m resolution of the Landsat data rendered very poor results. Based on the postulate that the water pixels behave like a smooth continuous surface, we increased the resolution to 5 m using minimum curvature interpolation. Two methods were tested for extracting the lake surface pixels: supervised classification and thresholding of the normalized difference water index. The results show that the interpolated Landsat data compared well with a high resolution Ikonos image of the same date and can improved the contouring of water bodies. For extracting the water pixel the classification approach performed better by about 15%. Statistical tests showed that the lakes have been systematically decreasing but that these changes cannot be attributed to climatic factors.

RÉSUMÉ:

La disponibilité en eau est soumise à une dynamique complexe impliquant la fluctuation du niveau de l'aquifère, elle-même soumise à des facteurs climatiques et édaphiques, ainsi qu'au couvert et à l'utilisation du sol. La pression humaine peut avoir un effet drastique sur le niveau des aquifères, dont l'effet n'est souvent perceptibles qu'après des années d'utilisation continue. Dans cet article, nous utilisons une séquence temporelle de 50 images Landsat pour l'étude d'un complexe de petits lacs dans le nord du Minas Gerais. Notre objectif est de quantifier les fluctuations de l'aquifère pour la période 1984-2009 par le suivi bi-annuelle de l'aire de ces lacs et de les comparer au bilan hydrique afin de comprendre leur évolution. N'ayant aucune mesures du niveau de l'aquifère, nous avons développé une méthodologie basée entièrement sur la télédétection et les données météorologiques. Comme ces lacs sont très petits, la résolution de 30 m des données Landsat donnait de piètres résultats. En se basant sur le postulat que les pixels d'eau se comportent comme une surface lisse et continue, nous avons augmenté la résolution à 5 m par interpolation de courbure minimale. Deux méthodes ont été testées pour l'extraction des pixels surface du lac: la classification supervisée et l'application d'un seuil sur l'indice différentiel normalisé de l'eau. Les résultats montrent que les données interpolées Landsat se comparent bien avec une image Ikonos de haute résolution de la même date et permettent d'améliorer l'extraction du contour des plans d'eau. Pour extraire les pixels d'eau, la classification supervisée a fourni des résultats à peu près 15% supérieurs. Des tests statistiques ont montré que les lacs ont systématiquement diminué, mais que ces changements ne peuvent être attribués à des facteurs climatiques.

1 INTRODUCTION

The watershed of the Peruaçu River hosts two important protected areas totaling over 80,000 ha yet it suffers from strong human pressure for water which is the most sought resource in this semiarid zone. In particular, the Veredas do Peruaçu State Park is apparently suffering from continuous lowering of its aquifer which is observable from the few small lakes inside the park and one larger lake outside. Although the phenomenon is quite obvious to the local population, it still needed to be demonstrated in a scientific non-refutable manner. One such argument is that the lowering could be caused by local changes in the precipitation and water balance (AW). Since no records of the level of the aquifer or the lakes are available for the past, we had to develop a methodology entirely based on historical remote sensing and meteorological data to unambiguously demonstrate and quantify the phenomenon.

Although human occupation can be considered sparse, but since the Peruaçu watershed is relatively small ($1450 km^2$) and the region receives almost no precipitation during seven months of the year, we argue that the pressure of the irrigation for agriculture, eucalyptus plantations and the numerous wells that have been dug in the past 30 years is too great for the capacity of the watershed.

A remote sensing multi-temporal approach was chosen to create a time sequence of images to monitor the size of the Peruaçu lakes and Landsat images stood as the most logical choice for analyzing the dynamics of these lakes for being the largest record of systematical remote sensing data available for civil use. Passive optical infrared images are also considered the most effective type of data for delineating water bodies since they absorb almost totally the incoming radiation and produce a sharp contrast with the surrounding vegetation and soil (Bonn and Rochon, 1992; Jensen, 2005).

Because the lakes under investigation are relatively small, the resolution of Landsat images is somewhat marginally acceptable when considering the mixed pixel problem. The fact that these water bodies are smooth continuous surfaces let us postulate that mixed border pixels have a predictable behavior and could be sub-sampled using some interpolation technique.

The objective of this article is to infer the dynamics of the fluctuations of the water level of the aquifer through the past monitoring of the successive receding and inflating of the open water surface of six lakes found in the *Veredas do Peruaçu State Park* and surroundings. To achieve this goal it was necessary to:

1. create a valid methodology for the extraction of the open water surfaces of these lakes from the historiacl series of past Landsat images knowing that there would not be any validation data for the past records;
2. establishing the relationship, if any, with the AW computed from meteorological data.

2 MATERIAL AND METHODS

Because our objectives have a twofold aspect, our methodology was also split. On one hand we needed to define a reliable approach to extract systematically the contours of the lakes in the long series of Landsat images given that we would only be able do validate the data for two of these images (using one high resolution image of 2006 a one geodetic survey of 2010). On the other hand we want to use the data extracted from these lake contours to cross with AW data to verify our hypotheses that the lakes surfaces are receding at an alarming rate.

2.1 Study Area

The study area (Figure 1) is located in Northern Minas Gerais - Brazil, a savannah region that can be marginally classified as semiarid with less than 900 mm of rain per year. The lakes under study are all inside or within the vicinities of the *Veredas do Peruaçu State Park*. The hydrographic network is part of the Peruaçu River Basin being a left tributary of the San Francisco River. Rainfall is unevenly distributed during the year and is mostly concentrated between November and March. The whole region is mostly flat with deep soils composed mostly of sand and less than 15% of clay that have a low capacity of water retention.

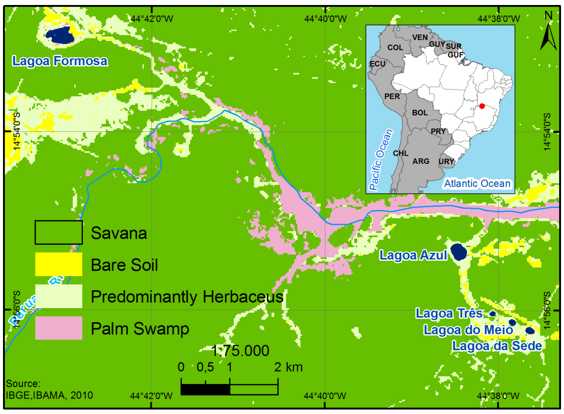


Figure 1: Location of the study area in Northern Minag Gerais.

The lakes themselves are small with the largest having an average area of around ten hectares. Six lakes are analyzed in this article; they are from the largest to the smallest: *Lagoa Formoza*, *Lagoa Azul*, *Ladoa da Sede*, *Lagoa do Meio*, *Lagoa Três* e *Lagoa da Pista* (now dry) (Figure 1. Although there has been a few hypothesis to explain the genesis of these lakes and their relative alignment, no conclusive results were ever presented. The last of these lake (*Lagoa da Pista*) had open water until 2000 but has dried up and is now but an intermittently saturated herbaceous round field. Unofficial reports by the local population all outline the gradual decrease of the open water surface of most of these lakes but no actual study was ever undertaken.

Until the 1970s the region was occupied by small family groups descended from the Indian tribe *Xacriabá*. In the middle of that decade the Brazilian government offered subsidies and incentives to companies that were willing to invest in eucalyptus plantations for wood supply. This was also the beginning of a much denser occupation of the area by workers and farmers. The impacts of the plantations were reflected in the decrease of biodiversity, both in terms of fauna and flora, and also by an increased pressure on water resources. Plantings occurred until the early 1990's, then the companies abandoned the planting of eucalyptus in the region due to the low productivity of the plantation that was not well adapted to the natural conditions. The region was recognized as having unique biological characteristics and the Brazilian authorities created a national park (*Cavernas do Peruaçu*) and a state park (*Veredas do Peruaçu*) to protect the natural beauties and the archeological heritage (rock paintings) of the Peruaçu watershed (Maillard et al., 2009). Although the area is now protected by law, the effect of the previous uses can still be observed and the area surrounding the parks still suffer from human pressure, especially on water.

2.2 Data and data pre-processing

Landsat images. Images from Landsat-5 TM were chosen for the obvious reason that they constitute the largest multi-temporal image bank existing today. Landsat-5 has been continuously collecting image data for the past 26 years. The period considered by this research starts in 1984 and ends in 2009. In all, 53 images were acquired from Landsat-5 TM and two from Landsat-7 ETM+, all for the orbit/scene 219/70 (World Reference System). Table 1 shows the exact dates for the images. The dates of the image correspond ideally to the end of the wet season (first image) and the end of the dry season (second image) but had to be slightly shifted in cases where images were either of low quality (clouds) or unavailable.

Year	1^{st} image	2^{nd} image	Year	1^{st} image	2^{nd} image
1984	13/jun	13/oct	1998	20/jun	26/oct
1985	31/may	06/oct	t1999	19/mar	11/sep
1986	15/mar	09/oct	2000	24/apr	15/oct
1987	02/mar	12/oct	2001	24/mar	01/oct
1988	21/apr	30/oct	2002	20/apr*	13/oct*
1989	Excluded	Excluded	2003	20/jul	08/oct
1990	10/mar	20/oct	2004	01/apr	24/sep
1991	30/apr	07/oct	2005	04/apr	13/oct
1992	18/may	23/sep	2006	20/jun	30/sep
1993	18/mar	12/oct	2007	Excluded	03/oct
1994	22/apr	12/aug	2008	24/feb	05/oct
1995	24/apr	02/oct	2009	14/mar	06/sep
1996	26/mar	20/oct	2010	4/may**	
1997	09/feb	07/oct			

Table 1: List of Landsat images (* indicates Landsat-7, the rest are Landsat-5; ** the 2010 image was only used to validate the lake contour extraction method).

The images had to be geometrically and radiometrically corrected and an atmospheric compensation also had to be applied. The geometrical correction was done with an "image-to-image" approach using a one-meter Ikonos image as basis (which was geometrically adjusted using control points from a geodetic GPS survey). The atmospheric and radiometric correction were applied using an in-house program build for that purpose: *Corat_Landsat*. The program takes as input a table containing 1) the name of the image file, 2) the DN value for the dark object substraction (Chavez Jr., 1988) for bands 1, 2, 3, 4, 5 and 7, 3) the sun elevation angle and 4) the sun-earth distance in astronomical units. The output is a 16 bit reflectance image (reflectance values were redistributed between 0 and 10 000).

Meteorological data - Water balance. The calculation of the AW was first proposed by Thornthwaite in 1948 and improved in 1955 (Thornthwaite and Mather, 1955). The main objective of the methodology is to determine the hydraulic characteristics of a given region without direct measurements on the ground (Pereira, 2005). The water balance is the simple budget between input and output of water within a watershed:

$$\Delta S = \left(\underbrace{P + G_{in}}_{Inflow}\right) - \left(\underbrace{Q + ET + G_{out}}_{Outflow}\right) \quad (1)$$

where P is the precipitation, G_{in} and G_{out} represents the ground water flow, Q is the runoff water and ET is the evapotranspiration.

The Thornthwaite procedure simplifies the AW calculation by estimating all its components from only two input parameters: average daily temperature and precipitation:

$$AW_t = AW_{t-1} exp\left(-\frac{PET_t}{AWC}\right) \quad (2)$$

where AW_t is the available water at time t, AW_{t-1} is the available water at time $t-1$ (in our case we set set t to be every ten days), PET_t is the potential evapotranspiration at time t and AWC is the soil's water holding capacity. The water balance can be summarized in three situations.

- $\Delta P < 0$; net precipitation (precipitation - potential evapotranspiration) is less than zero: the soil is drying.
- $\Delta P > 0$ but $\Delta P + AW_{t-1} \leq AWC$; net precipitation is more than zero but net precipitation plus the available water from time $t-1$ is less or equal than the soil's water holding capacity: soil is wetting.
- $\Delta P > 0$ but $\Delta P + AW_{t-1} > AWC$; net precipitation is more than zero and net precipitation plus the available water from time $t-1$ is more than the soil's water holding capacity: soil is wetting above capacity and water goes to runoff.

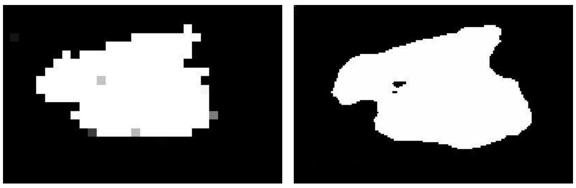
2.3 Extraction of lake contours

Water in liquid form is usually well contrasted from its surrounding dry(er) land unless it is overshadowed by vegetation cover like mangroves, flooded forests or aquatic plants (Caloz and Puech, 1996) . In many cases, a simple threshold in an infrared image histogram can reliably separate water from the other land covers with a relatively good rate of success and investigators have developed simple techniques for doing so in a systematical manner (Bryant and Rainey, 2002; Jain et al., 2005). Histograms of near infrared images containing a fair amount of open water surfaces are usually bimodal with the first peak directly related to water. Yet, when one looks closer, the water-land limit is often blurred by a varying width occupied by aquatic plants that can fluctuate over various time scales (yearly or seasonally). Using a sequence of historical Landsat images for which we had no validation data, we needed to have a very strict definition of the water-land interface. We defined the lake "water-margin" as the point at which water overwhelmingly dominates the surface and estimated that point to correspond to 70-80%.

2.3.1 Resampling through interpolation: Another source of error comes from the mere sampling resolution of 30 meters used by the TM and ETM sensors. Although not considered an issue when measuring an ocean of a large lake, it rapidly becomes a problem when studying very small lakes such as the ones found in the VPSP that range from just over ten hectares to just under one hectare. In these small lakes, the number of mixed pixels can represent a large proportion of the total lake pixels (up to about 35% in the case of the smallest lake). A half pixel shift in image registration could signify an important difference in water pixel count.

Scale (or spatial resolution) can have various effects on image classification accuracy. A finer resolution can usually decrease the proportion of pixels falling on the border of objects (hence less mixed pixels) which can result in less classification confusion. Conversely, a finer resolution will generally increase the spectral variation of objects that can, in turn increase classification confusion (Markham and Townshend, 1981). Fortunately, water (especially clear and deep) is spectrally a relatively smooth surface for which a finer resolution will bring more benefit (less border pixels) than disadvantage (spectral variation). Based on the fact that water is spectrally smooth and that it strongly contrasts with dry land, we argue that artificially increasing the resolution of an image containing water surfaces can generate a better definition of the water-land limit. To do so, a number of tests were prepared to define an appropriate interpolation method to resample the images.

Amongst the various interpolation methods we opted for the minimum curvature interpolation (a variation of bi-cubic spline) with tension as described in Smith and Wessel (1990). This interpolation method has the advantage of being able to generate a smooth surface without generating undesirable fluctuations (artifact peaks or dips) by using a tension parameter. This interpolation proved better than "inverse distance weighted" that tends to produce artifact dips between sampling points (Maune et al., 2001). The minimum curvature worked well and fast and generated smooth ramps while keeping a sharp water-land edge. Figure 2 illustrates the effect of interpolating the Landsat data to 5 m on the lake extraction processing.



(a) 30 m (b) 5 m

Figure 2: Comparison of the lake extraction methods using the original 30 m Landsat data (a) and the 5 m interpolated data (b).

2.3.2 Calssification: Because of the nature of our study, unsupervised and automatic segmentation methods were discarded. These approach are most suited with single date image applications when terrain validation is possible. Two supervised methods were then chosen: 1) enhanced image classification and 2) thresholding the normalized difference water index (NDWI; McFeeters, 1996; Ji et al., 2009).

Image Classification. Traditional image classification is carried out on a pixel-by-pixel basis. Although an increasing number of studies show that region-based or object-based classification tends to improve results significantly, it was not judged necessary in this particular case for two main reasons. First because of the spectral nature of water being a smooth surface with small variations (at least in the optical infrared) and secondly because these methods usually offer little control over what is defined as an object. Conversely, classification approaches such as Maximum likelihood can produce posterior probability maps that can be thereafter thresholded (hardened). The latter approach had the advantage to require training data only for the object of interest whereas classical classification procedures require all classes to have been defined using training data. In this case we opted for the posterior probability which can be simplified as the Gaussian probability density of the "water class". In simple nominal classification, a pixel can be classified as pertaining to a particular class even if its probability is low, as long as it is higher than for all the other classes. By using a high threshold value (i.e. $> 90\%$) to attribute a water label to a pixel, we are able to use but a single class and avoid having to gather training data for other objects or surfaces.

NDWI threshold. Using the same logic as the normalized difference vegetation index (NDVI) the normalized difference water index (NDWI) was proposed by McFeeters (1996) as a means to separate water from other surfaces (Eq. 3).

$$NDWI = \frac{\rho_{green} - \rho_{NIR}}{\rho_{green} + \rho_{NIR}} \tag{3}$$

where ρ_{green} is the green reflectance (Landsat TM band 2: $0,52-0,60\mu m$) and ρ_{NIR} is the near infrared reflectance (Landsat TM band 4: $0,77-0,90\mu m$). The NDWI varies between -1 and 1 and uses zero as the threshold between land (≤ 0) and water (> 0). A number of variations were later proposed for NDWI. In their article, Ji et al. (2009) compared a number of these variations applied to Landsat, ASTER, SPOT and MODIS images. They found that the modified NDWI (MNDWI) proposed by Xu (2006) performed better (Eq. 4).

$$MNDWI = \frac{\rho_{green} - \rho_{SWIR}}{\rho_{green} + \rho_{SWIR}} \tag{4}$$

where ρ_{SWIR} is the reflectance in short wave infrared (Landsat TM band 5: $1,55-1,75\mu m$).

2.4 Validation and Statistical Testing

Two validation data sets were unsed for testing the performance of the extraction of the lake contours from the interpolated Landsat data which also involved our definition of the "water-land" edge. First, the contours from the dry season image of 2006 were compared against the contours extracted from a fusionned Ikonos image (1 m) five days apart form the Landsat image. Secondly, the four lakes of the VPSP (data from the larger lake outside the park could not be acquired) were surveyed using a geodetic GPS in kinetic mode to be compared with the contour from the Landsat image (with a five days difference). Coordinates of the lake contour were acquired at an interval of 15 meters with an approximate precision of 10 cm.

The validation was done by two complementary methods: 1) by expressing the difference between the areas as a proportion of the validated area ($\frac{A_{real}-A_{observed}}{A_{real}} \times 100$); and 2) by overlapping the two contours (interpolated Landsat and validation data) and dividing the overlap area (intersection) by the merged areas (union) of both contours as illustrated in Figure 3.

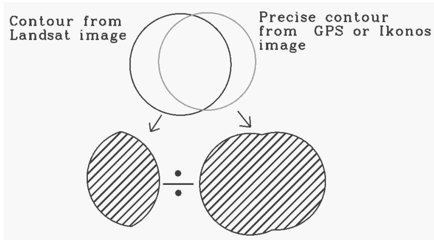


Figure 3: Validation method for testing the accuracy of the lake contours extracted from the interpolated Landsat images.

The statistical testing consists in establishing the strength of the relationship between the areas of all six lakes and the AW of the same period as the images. Although the response of the water level is not spontaneous, the trend should still be statistically perceptible. Because the areas of the lakes are not normally distributed, a regression was not recommended. Spearman's correlation does not assume a normal distribution of the dependant variable and was chosen instead. The correlation was also computed between the area of the lakes themselves as a mean to infer a generalized trend.

3 RESULTS AND DISCUSSION

3.1 water balance

The AW was calculated for the period 1983 - 2009 using the Thonthwaite method trimonthly (the year 1983 was added in order to feed the Available Water for the beginning of the 1984 budget). Figure 2 shows the annual budget averaged every five years for the period along with the average budget for the whole period (white line). Apart from the two first periods (1984-1989 and 1990-1994) which appear as exceptionally high and exceptionally low respectively, the other periods do not show any trend towards an increase or a decrease.

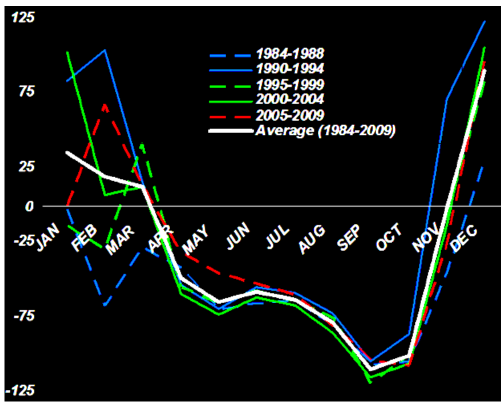


Figure 4: water balance averaged for every five years between 1984 and 2009 and overall average (white line).

3.2 Lake Contours Extraction and validation

The 50 selected Landsat images were geometrically corrected, registered to a UTM grid, corrected for atmospheric interferences (using Chavez's DOS method) and transformed in reflectance values. The images were also interpolated to a 5 m resolution using the minimum curvature algorithm. It is visually striking to see that, apart from a few exceptions, the multi-temporal dataset shows an almost constant shrinking of the lake surfaces and even the disappearance of one small water body. Figure 5 illustrates the difference in lake surfaces for the whole period. The triangular area at the bottom of the 1984 image, was part of the eucalyptus plantation and is now regenerating.

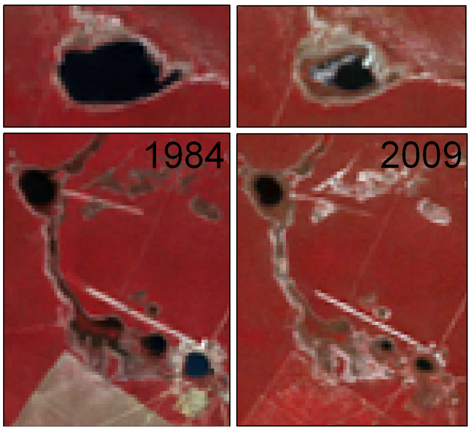
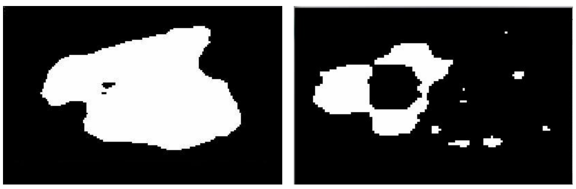


Figure 5: Comparison of the lakes for the same time of the year in 1984 (left) and 2009 (right).

Two lake extraction methods were used: 1) threshold of the posterior probability of the maximum likelihood classification and 2) threshold of the modified normalized difference water index (MNDWI). The former approach yielded far superior results in almost all images. We attribute this result to the presence of aquatic vegetation and turbidity (for the Formosa lake) mixed with the water which tends to increase reflectance in the near and mid- infrared. Figure 6 shows the extreme example of the Formosa lake which is outside the State Park and suffers from eutrophication and aquatic vegetation bloom. Figure 6 should also be compared with the false color image at the top right of Figure 5.



(a) Classification - 5 m (b) NDWI threshold - 5 m

Figure 6: Comparison of the contour extraction methods using classification (a) and MNDWI threshold (b).

By using the posterior probability of a single water class, we found that there was always an easily identifiable break between the water and non-water classes that made the selection of a threshold very easy. The threshold was applied to all 50 images and the area of all six lakes computed for every date. The graph in Figure 7 shows how these areas have changes between 1984 and 2009. Table 2 gives an over view of the shrinking of the six lakes. The lake areas of 1990 are also indicated for being the record size for all lakes. While lake "Pista" has completely disappeared since 2000, four other lakes have lost between 59 and 80% of their area. The lake "Azul" has somewhat retained much more of its original area (loss of 29%) and it is also the only lake surrounded by hydromorphic gley soil with a higher clay content.

Since we did not have reliable elevation data at the time of writing, the areas water surfaces could not be associated with precise

Areas			Lakes			
km^2	Pista	Três	Meio	Sede	Azul	Formosa
1990	4962	28778	37413	56402	105389	296237
1984	375	14795	32471	39030	92670	291502
2009	0	2928	7228	12243	65829	170409
% loss	100%	80,2%	77,7%	68,6%	29,0%	58,5%

Table 2: Comparison of the areas of all six lakes between 1984 and 2009 with the shrinking expressed in percentage (1990 was the record year for all lakes).

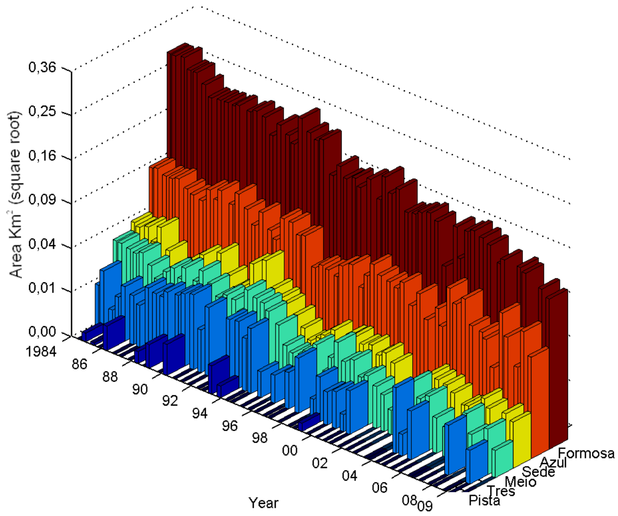


Figure 7: Graph showing the evolution of the area of all six lakes for the period 1984-2009.

altimetric level measurements. These data will be available at the third quarter of 2010. Using the digital elevation model (DEM) from the ASTER sensor, and overlaying the contours over it we were able to estimate the lowering of the water level for the 1984-2009 period to about 1 meter for the lake "Azul" and to slightly over 2 meters for the lakes "Sede", "Meio", "Três" and "Formosa", being outside the State Park. Figure 8 shows the 1984 and 2009 levels on the ASTER DEM profile.

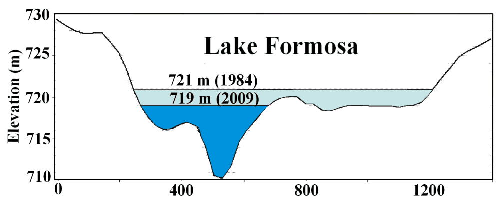


Figure 8: Water level differences between 1984 and 2009 on an ASTER DEM profile for lake "Formosa".

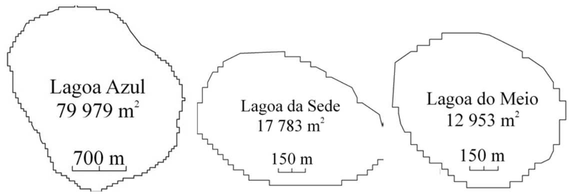
The validation of the data was done using the approach described in section 2.4. Table 3 shows the validation obtained with both control datasets (GPS and Ikonos image) and with the two methods of comparison (simple comparison of areas and "intersection ÷ union" approach). As expected, the accuracies with the latter method are slightly lower but since all accuracies but two are well above 80%, we conclude that both our extraction method and our geometric correction are within very acceptable boundaries. Figure 9 shows the contours extracted from the Landsat image of 2010 and the GPS survey coutours for three of the lakes.

3.3 Statistical Testing

Spearman's correlation test was applied to the area series of all lakes along with the AW data for the same period. The results

Lakes	**Area Comparison**		**Intersection/Union** $\times 100$	
	GPS	Ikonos	GPS	Ikonos
Três	94,54%	n/a	81.05%	n/a
Meio	93,34%	86,01%	91,53%	71,04%
Sede	89,50%	94,41%	89,16%	83,85%
Azul	94,18%	96,36%	92,13%	93,20%
Formosa	n/a	95,08%	n/a	92.66%

Table 3: Validation of the lake contour extraction using the GPS survey and the Ikonos scene. Column 2 and 3 show the results for the area comparison; column 4 and 5 show the accuracy obtained with the $\frac{intersection}{union} \times 100$ approach.



(a) Landsat lake contours

(b) Geodetic GPS lake contours

Figure 9: Comparison of the contours of three of the six lakes using the interpolated Landsat data (left) and the geodetic GPS survey data (right).

are presented in Table 4. The only correlation between the areas of the lakes and the AW is with the "Pista" lake which has dried up since 2000 and the level of significance is p=0,05. Conversely, all the lakes are strongly related among themselves with a significance of 0,01. This confirms that the trend is statistically significant and that we can infer that the lakes are rapidly shrinking. Even lake "Azul" which has kept a much more constant surface area is strongly correlated with all the other lakes (0,601 to 0,871). Since the AW cannot be said to be correlated with the shrinking of the lakes, the meteorological explanation becomes much less plausible and the human pressure on the watershed can more easily be pinpointed as responsable.

Table 4: Results of the Spearman's correlation tests.

		AW	**Lakes**				
			Pista	Três	Meio	Sede	Azul
Pista	Corr.	*0.329					
Três	Corr.	0,209	**0,455				
Meio	Corr.	0,209	**0,611	**0,834			
Sede	Corr.	0,075	**0,566	**0,735	**0,957		
Azul	Corr.	0,259	**0,601	**0,871	**0,866	**0,789	
Formosa	Corr.	0,068	**0,524	**0,674	**0,899	**0,897	**0,730

* Significant at 0,05
** Significant at 0,01

4 CONCLUSIONS

Multi-temporal remote sensing offers countless opportunities for monitoring past and present changes in land cover and land use. By monitoring the size and shape of water bodies, we can infer on human pressure and climate change. In this article we proposed an innovative approach for monitoring small lakes using medium resolution Landsat data. The approach uses minimum curvature interpolation to artificially improve the resolution of the image data and produce a much cleaner lake contour that matches the actual measured contour with a high success rate (15 validation out of 16 with better than 80% and 10 better than 90%). Using posterior probability of a maximum likelihood classifier, we were able to systematically extract contours from six lakes for 50 different dates with ease and good matching of control data. The Modified Normalized Difference Water Index (MNDWI) did not perform well for these small shallow lakes with the presence of aquatic vegetation. The water balance using the Thornthwaite approach is well suited for area with limited climatological information and provides valuable insight on the climatological condition ruling water availability. In this study, the water balance could not be statistically correlated (Spearman's correlation) to the shrinking of six small lakes in Northern Minas Gerais, Brazil.

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