QUANTIFICATION OF FLOODED AREAS OF PANTANAL BY SUB-PIXEL CLASSIFICATION OF MODIS TIME-SERIES DATA

João Francisco Gonçalves ANTUNES[1]
Júlio César Dalla Mora ESQUERDO[2]

Abstract

Floods in the Pantanal affect the fish production and influence the dynamics of vegetation, also changing the meat production. The understanding of floods dynamics is crucial to infer the level of flooding, once it promotes changes in the whole plain. The understanding of floods dynamics is crucial to infer the level of flooding. MODIS (Moderate Resolution Imaging Spectroradiometer) images provide wide coverage of the Earth's surface with high temporal resolution, which are important features for flood monitoring. However, its moderate spatial resolution may cause the spectral mixing of different land cover classes within a single pixel. In this context, the objective of this study was to apply a methodology for sub-pixel classification using MODIS time-series data, in order to quantify the flooded areas in the Pantanal. Data from the mid-infrared channel of MODIS sensor allowed the monitoring of flood prone areas in the Pantanal during the 2008/2009 and 2007/2008 hydrological years. The drought and flood periods are quite variable, occurring from North to South and from East to West. The sub-pixel classification models, generated from Fuzzy ARTMAP neural network, demonstrated excellent suitability for the mapping and quantification of flooded areas of the Pantanal based on the Commitment measure.

Keywords: Remote sensing. Image processing. Wetlands. Pattern recognition. Neuro-fuzzy networks.

Resumo

Quantificação de áreas inundadas do Pantanal por meio da classificação sub-pixel de séries temporais de dados MODIS

As inundações no Pantanal condicionam a produção de peixes e influenciam a dinâmica da vegetação, afetando a criação de gado bovino. O entendimento da dinâmica das inundações é de fundamental importância para inferir sobre o nível das cheias, já que causam mudanças em toda a planície. As imagens do sensor MODIS (*Moderate Resolution Imaging Spectroradiometer*) fornecem uma ampla cobertura da superfície da Terra com alta periodicidade, que possibilitam o monitoramento das inundações. Entretanto, a sua moderada resolução espacial faz com que possa ocorrer a mistura espectral de diferentes classes de cobertura da terra dentro de um mesmo pixel. Nesse contexto, o objetivo do trabalho foi aplicar uma metodologia de classificação sub-pixel utilizando séries temporais de dados MODIS para quantificar as áreas inundadas do Pantanal. Os dados da banda do infravermelho médio do MODIS possibilitaram o monitoramento de áreas inundadas no Pantanal durante os anos hidrológicos de 2007/2008 e 2008/2009. O período de seca e enchente é bastante variável, ocorrendo de norte para sul e de leste para oeste. Os modelos de classificação sub-pixel, gerados pela rede neural Fuzzy ARTMAP, demostraram excelente adequação para o mapeamento e quantificação das áreas inundadas do Pantanal baseado na medida de Compromisso.

Palavras-chave: Sensoriamento remoto. Processamento de imagens. Áreas úmidas. Reconhecimento de padrões. Redes neuro-fuzzy.

[1] Embrapa Informática Agropecuária, Pesquisador, Caixa Postal 6041 - 13.083-886 - Campinas - SP, Brasil. E-mail: joao.antunes@embrapa.br

[2] Embrapa Informática Agropecuária, Pesquisador, Caixa Postal 6041 - 13.083-886 - Campinas - SP, Brasil. E-mail: julio.esquerdo@embrapa.br

INTRODUCTION

The Pantanal is worldwide the largest continuous floodplain and houses a large concentration of wildlife. Extensive livestock, fishery and tourism are the main economic activities in this region, conducted in close relationship with the natural environment. The frequency of seasonal inundation, representing a regime of floods and droughts, conditions the fish production and influences the dynamics of vegetation, affecting the beef cattle livestock (PADOVANI, 2010).

Due to both the large extension of the Pantanal and the difficulties for accessing it, satellite images are important instruments for the analysis of inundations, providing a synoptic view of the entire region.

The MODIS (Moderate Resolution Imaging Spectroradiometer*)* sensor, aboard the orbital platform from the international EOS program (Earth Observing System), managed by NASA (National Aeronautics and Space Administration), generate the data processed for environmental studies. The TERRA satellite, launched in December 1999, crosses the Equator at 10:30 am (local time), in descending orbit (SOARES et al., 2007).

MODIS data has moderate spatial resolution, high repeatability, good radiometric quality, high geometric precision, atmospheric correction and free distribution. This kind of data presents high potential for applications to monitor the spectral dynamics of flooded areas from the Pantanal over time (SANTOS et al., 2009).

In this research line, recent studies have been carried out using MODIS time-series data in areas susceptible for inundation in the Southern Pantanal (GOLTZ et al., 2006), for the evaluation of the spatial-temporal dynamics of Pantanal biome (ADAMI et al., 2008), for the characterization of seasonal inundation patterns in Everglades, Florida, (ORDOYNE; FRIEDL, 2008) and at the temporal evaluation of flooding changes at Lake Poyang in China (FENG et al., 2012).

The presence of water can be detected by remote sensing, due to the very characteristic behavior of inundated areas, with a high absorption of radiation in almost all electromagnetic spectrum bands (ANTUNES; ESQUERDO, 2007). Nevertheless, the spectral mixture of different land cover classes may occur when the pixel size is larger than the land features, where the radiometric measurement represents a combination of reflectance from all targets within this pixel, which may cause problems of detailing for a reliable quantification of inundated areas from the Pantanal.

Artificial intelligence in remote sensing can be conceived of as the state of the art. There are few studies related to the use of machine learning techniques for image classification (GIACCO et al., 2010). In this sense, new approaches of artificial intelligence, combining neural networks and fuzzy logic for pattern recognition to classify time-series of satellite images, are a timely, viable and innovative alternative for the sub-pixel analysis.

In this context, the objective of this study was to quantify the flooded areas from the Pantanal*,* considering a sub-pixel classification of MODIS time-series data, based on neuro-fuzzy networks, during the hydrologic years 2007/2008 and 2008/2009.

MATERIALS AND METHODS

This study was done in the brazilian part of the Pantanal*,* which is an alluvial floodplain with an extension of 138,183 km^2, localized in the watershed of the Alto Paraguai river. From its territory, 65% are located in Mato Grosso do Sul State and 35% at the Mato Grosso State, as illustrated at figure 1, which also presents the four areas chosen for the analysis of the results from the inundation dynamics.

Figure 1 - Brazilian Pantanal Floodplain and the four areas prone to flooding

The Pantanal is periodically flooded by the Paraguai river and its tributaries, every year, during the rainy season, due to its low altitude (80-150 m) and plain slope. The flood period in the Pantanal occurs generally between March and September and the drought season extends from October till February (JUNK et al., 2006).

The TERRA satellite time-series images were obtained from the MODIS Brazilian States Database (EMBRAPA INFORMÁTICA AGROPECUÁRIA, 2014), which stores and makes available at Internet images of product MOD13Q1, for brazilian states, in a geographic projection, datum WGS-84 and in GeoTIFF format (ESQUERDO et al., 2010).

The product MOD13Q1 consists of pixel compositions with high radiometric quality, improved observation geometry, minimum presence of clouds and aerosols, selected from daily images along 16 days. The actual version is collection 5, which got sensitive changes in order to increase the data quality (LATORRE et al., 2007).

Water has a low spectral response in the range 0.38 - 0.70 µm of the electromagnetic spectrum. Outside this spectral range, the reflectance is zero and there is total absorption, which shows that water is a strong radiation absorber, in almost all spectral bands, although this behavior could be a little changed, due to water turbidity and depth. Vegetation and bare soil have always higher reflectance than the water (COLWELL, 1983). In inundation prone areas, the variation of the water height can affect the behavior of land cover, during the hydrologic cycle of the Pantanal, and there is a spectral mixture of these pixels in time, especially on images with moderate spatial resolution.

Based on these evidences, in this study we used those reflectance data of band 7, mid-infrared (MIR) of MODIS satellite, in the spectral range 2.105 - 2.155 µm, at resampled spatial resolution of 250 m from MOD13Q1. Due to the wavelength of MIR from MODIS, this band is less influenced by aerosols in the atmosphere and more sensitive to the presence of water on the Earth surface.

The classification of MIR MODIS time-series was done with the self-organizing neural network of clustering Fuzzy ARTMAP, which is a non-parametric model based on the Adaptive Resonance Theory of cognitive processing from the human brain, destined to the approximation of non-linear multi-dimensional functions. This architecture acts recurrently to solve the "stability-plasticity dilemma". It keeps equilibrium to create new recognition categories, when unknown patterns stimulate the network and the capacity to group similar patterns in the same category, preserving the previous acquired knowledge (CARPENTER et al., 1991).

The Fuzzy ARTMAP neural network is composed by an ART_a module, which processes the input data, and an ART_b module, that processes the output response desired for the pattern presented to the network, whose elements are values from the fuzzy sets, connected by a module of associative memory, which makes the connection between the recognition categories from ART_a to ART_b. The supervised training of Fuzzy ARTMAP is done with the competitive learning the "winner-take-all" rule and the strategy to vote on the most frequently activated neurons for different data ordination, in order to maximize the generalization of pattern recognition categories, and to minimize the errors of network prediction (CARPENTER et al., 1992; MANNAN et al., 1998).

For sub-pixel classification was used the algorithm of the Fuzzy ARTMAP neural network based on the Commitment (CMT) measure, which expresses the degree of commitment of a pixel related to a certain class, being very similar in character to Bayesian posterior probabilities. (LI, 2007; 2008). The Fuzzy ARTMAP neural network and the sub-pixel classification algorithm of the Commitment measure used for this research are part of a suite of classifiers from the IDRISI software (CLARK LABS, 2014).

For the delimitation of the training samples to be used by the Fuzzy ARTMAP classifier and for the validation of the CMT classification models, a thematic reference map of flooded areas was made. It was generated based on vegetation data cover of the Pantanal biome, originated from the Project for the Conservation and Sustainable Use of the Brazilian Biologic Diversity (PROBIO), coordinated by the Brazilian Ministry for Environment (MMA), using Landsat images from 2002 (SILVA et al., 2007).

In order to guarantee a reliable classification from the learning process of the Fuzzy ARTMAP classifier, the minimum size of the training set was defined, based on Canty (2010), according to the rule of thumb used by Van Niel et al. (2005), calculated by Equation (1):

$$n \approx 30 \times N \times K \tag{1}$$

where:

n = training samples in all;

N = data dimensionality;

K = number of classes.

Being:

N = 23 images of MIR MODIS time-series, for each hydrologic year;

K = 2 classes (Water and Non-water).

Then:

$n \approx 30 \times 23 \times 2 = 1{,}380$ pixels.

From the input images and the training samples, the Fuzzy ARTMAP classifier with the sub-pixel classification CMT algorithm generates a set of images expressing information of the membership, being one for each class (Water and Non-Water). The degree of commitment of the pixels are measured between zero and one, which allows the estimation of water proportions in the pixels, by a matrix operation of zonal statistics, according to Equation (2):

$$A_{water} = A_{pixel} * \sum_{i=1}^{n} CMT_{water_i} \tag{2}$$

where,

A_{water} = flooded area (km^2);

A_{pixel} = MODIS pixel area of 0.0625 km^2 (250 m x 250 m = 62,500 m^2);

CMT_{water_i} = Commitment measure CMT for class Water by pixel;

n = number of internal pixels to the vector borders of the Pantanal.

For the validation of the suitability of CMT classification models for class Water, generated by Fuzzy ARTMAP, was used the ROC (Relative Operating Characteristic) curve, based on Pontius & Parmentier (2014). The ROC curve traces the rate of True Positives (TP) related to False Positives (FP) for different thresholds from the comparison between the commitment measures map with the reference map, representing the relation between the sensibility and the specificity of the classifier. The ROC value is the area under the curve (AUC), resulting from the connection of those points obtained for each threshold. AUC = 1 means that there is a perfect spatial agreement between the commitment measures map with the reference map, while AUC = 0.5 indicates the tendency of the commitment measures are distributed randomly. The ROC curve was calculated by an Excel electronic spreadsheet, developed by Pontius (2014), which is associated to the statistical modules of classification accuracy validation of the IDRISI.

RESULTS AND DISCUSSION

The Paraguai river is the main water collector of the Pantanal. After it receives the first rain, its flow is increased and the overflow starts to the floodplain, beginning the inundation. The natural hydrological cycle of the Pantanal starts in October and ends in September of the next year. The fluviometric measuring station (66825000) of the water height from Paraguai river, in Ladário - Mato Grosso do Sul State, is the main reference for the characterization of the hydrological regime from the Pantanal, indicating a period such as flood and drought (GALDINO; CLARKE, 1995).

Figure 2 shows the flood data from the Pantanal for the hydrologic years 2001-2002 till 2010-2011. When the maximum height of Paraguai river equals or exceeds the flood alert level, which is 4.00 m, it is considered as an inundation in the Pantanal, otherwise it is considered a drought. When the flood peak is situated between 4.00 and 4.99 m, it is considered a small inundation, between 5.00 and 5.99 m it is a normal inundation, and at 6.00 m or above it is a large inundation (GALDINO et al., 2002).

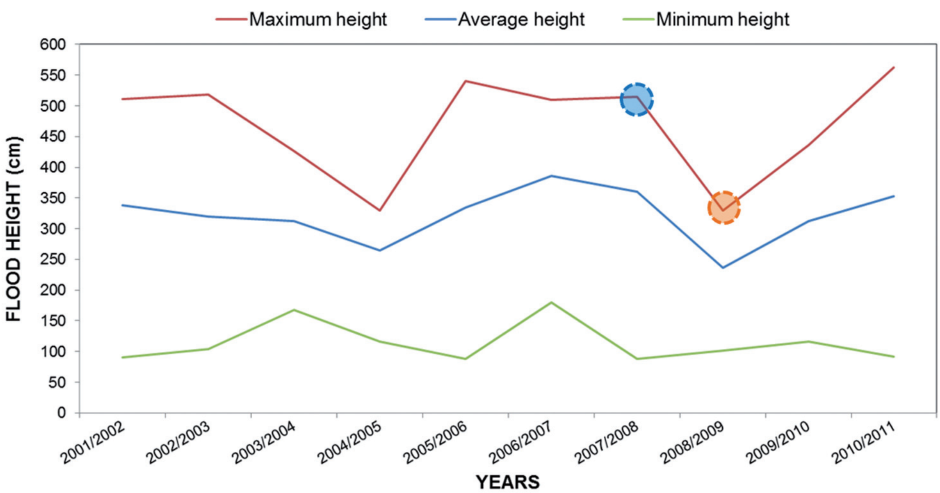

Figure 2 - Flood height of the Paraguay river in Ladário - Mato Grosso do Sul State for the hydrologic years 2001/2002 till 2010/2011

Source: MARINHA DO BRASIL (2012).

From the analysis of figure 2, it is possible to notice that during the hydrologic year 2007/2008 occurred pronounced inundations, while during hydrologic year 2008/2009 there was a strong drought, as indicated at the graphic.

MODIS image processing consisted on cutting the geographic borders of the Pantanal, obtained from a mosaic of Mato Grosso and Mato Grosso do Sul States. Then, MIR 16-day time-series compositions for the years 2007 to 2009 was made. In order to perform this task, the natural hydrologic cycle of the Pantanal was chosen from October 2007 to September 2008, and October 2008 to September 2009, with 23 compositions for each year, totaling 46 images.

For the generation of the MIR temporal profiles were delimited four areas prone to flooding, from distinct inundation times of the Pantanal, size 5 x 5 pixels, with approximately 1.7 km^2, represented at figure 1. The average profiles from these areas were extracted, in order to accompany, in an overall way, the evolution of the Pantanal inundations. The graphics which describe the temporal variation of the reflectance values from the MIR MODIS are presented at figure 3, for each one of the four inundation areas, along the hydrologic years 2007/2008 and 2008/2009.

The analysis of the graphics must be understood as an inverse logic from the flood regime, i.e., the reflectance peak value corresponds to the drought month, higher vegetation and bare soil presence, and to the lowest level of the flood month in the Pantanal, when the surface is inundated forming water bodies.

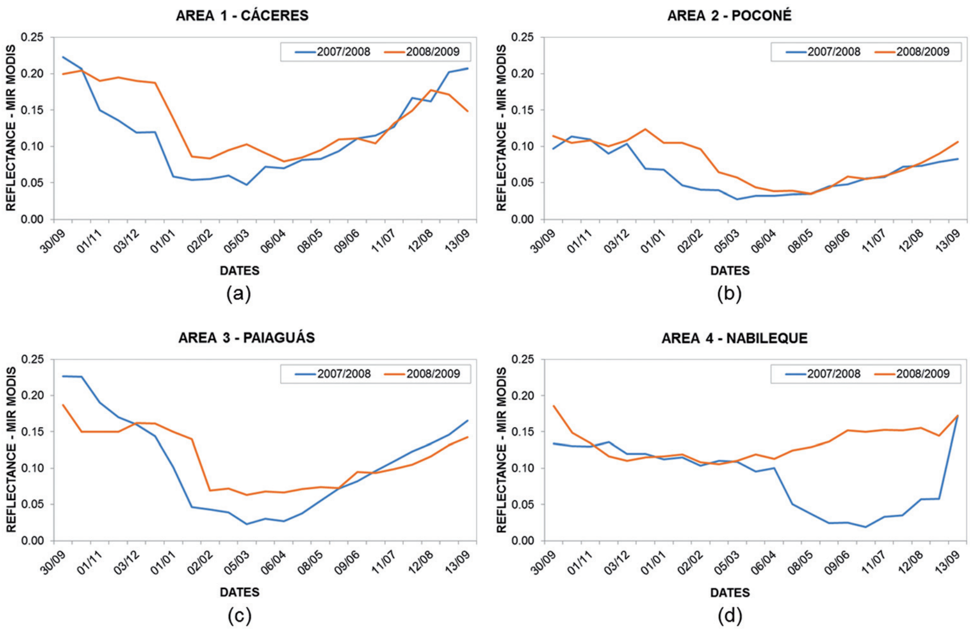

Figure 3 - MIR MODIS temporal profiles of the four areas prone to flooding along the hydrologic years 2007/2008 and 2008/2009

Figure 3 shows the variations on the MIR MODIS temporal profiles, originated from the inundation process in the four monitored areas. Such variations evidence differences due to both the time of the peak flows and the intensity of inundations which cause a strong variation on the water level. Generally the MIR values start very high and decrease when these areas are being flooded. From January to April these values are minimal, corresponding to the flood height, depending on the area analyzed.

Comparing the graphics referring to hydrologic years 2007/2008 and 2008/2009, variations of the lowest MIR values were identified during the peak of floods, reaching lower levels during the hydrologic year of pronounced inundation (2007/2008) and higher levels in the hydrologic year of strong drought (2008/2009), showing the sensitivity of MIR to the presence of water. Area 2 under study was an exception, whose the minimum MIR values were similar during both hydrologic years, since this region is located at the sub-region Poconé, at the confluence of Cuiabá and Paraguai rivers (SILVA; ABDON, 1998), with a high inundation frequency, even in drought years. Area 4 is a special case, it is located at the sub-region Nabileque, close to Paraguai river, whose flood peak in 2007/2008 occurred later but which in 2008/2009 probably was not inundated, since the MIR values increased at the same time.

An overall view from the analysis of MIR MODIS temporal profiles, shows that the inundations start in the northern Pantanal (Cáceres) with the water flow coming from the East (Paiaguás) to the West (Poconé). As the drainage occurs from these flooded areas, the inundations move to the southern region (Nabileque). After that, the Pantanal dries, till the cycle starts again during the next rainy season.

Data from PROBIO of the Pantanal biome were processed for the generation of the reference map, converting the scale to match the spatial resolutions of the different sensors used in this work. The vegetation cover classes identified as permanently flooded and influenced by river flooding, streams, lakes, saline, pioneer vegetation formations, riparian alluvial forest and alluvial Semi-deciduous Seasonal Forest were congregated in the class called Water and the other combinations included in class Non-Water.

Initially the vector of classes Water and Non-Water was transformed in an image with the spatial resolution of 30 m, scaled from 0 to 255 DN. Afterwards, based on Foody and Cox (1994), the image was degraded spatially with a low-pass convolution filter sized 9 x 9 pixels. This size is close to the ratio between the MODIS (250 m) and the Landsat (30 m) pixel size and resulting on a spatial resolution of 9 x 30 m equivalent to 270 m. Then this image was resampled by the nearest neighbor method to the size 0.002245º, compatible with the MODIS pixel of 250 m.

The result is an image with DN values between 0 and 255, where 255 represents those most homogeneous pixels of flooded areas, and consequently with less spectral mixture. For the delimitation of flooded regions, the following thresholds were defined of DN 200 to 255 for class Water, DN 2 to 199 for class Transition and 0 to 1 for class Non-Water. So the edge pixels are suppressed from class Water and the sample universe is constituted by homogeneous pixels from permanently flooded areas and influenced by flooding (ANTUNES, 2014).

To produce the set of samples as homogenous polygons, in order to help the learning process of the classifier, the sampling procedure from Antunes (2014) was executed, using the reference map at the 250 m spatial resolution, represented at figure 4.

Because there are naturally different proportions between classes Water and Non-Water, since they are unbalanced, sampling was executed with the proportionate stratified random technique, with minimum size defined as 0.050%. This technique involves the division of classes in homogenous subgroups, and afterwards selects a simple random sample at each subgroup, generating samples which are directly related to the size of classes. This processing selected 316 pixels from class Water and 844 pixels from class Non-Water totaling 1,164 pixels. Then a morphological dilation filter sized 3 x 3 pixels was applied with two iteration cycles to expand the areas around the central element, producing 7,868 pixels of class Water and 20,962 pixels of class Non-Water, totaling 28,830 pixels. Finally masking of the expanded areas was made which were overlapped among the classes, generating 7,441 pixels of class Water and 20,438 pixels of class Non-Water, totaling 27,879 training samples, which attends perfectly to the rule of minimum size defined previously.

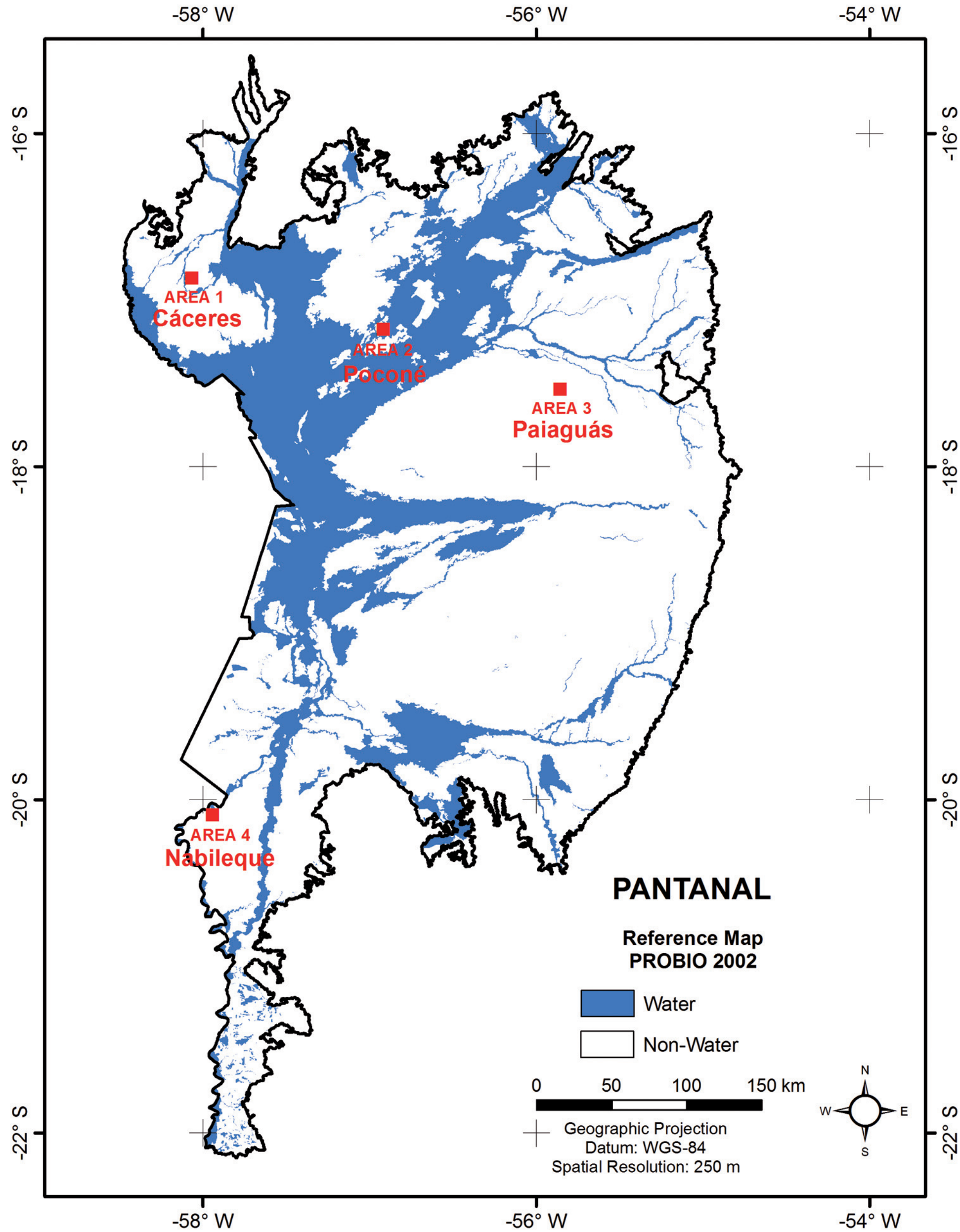

Figure 4 - Reference map of PROBIO 2002

The 23 images from MIR MODIS time-series were used as input variables of the Fuzzy ARTMAP classifier for each hydrologic year, with the training samples generated from the reference map. The configuration used for ART_a was the choice parameter 0.01, learning rate of 0.93 and the vigilance parameter equivalent to 0.94. For ART_b both the learning rate and the vigilance parameter were equal to 1.00. Within the adjustment simulations, this was the optimum combination of best model generalization. The map layer which connects ART_a to ART_b has two dimensions referring to classes Water and Non-Water. For the sub-pixel classification the Commitment measure CMT was used. Figure 5 illustrates the interface of Fuzzy ARTMAP classifier from IDRISI package.

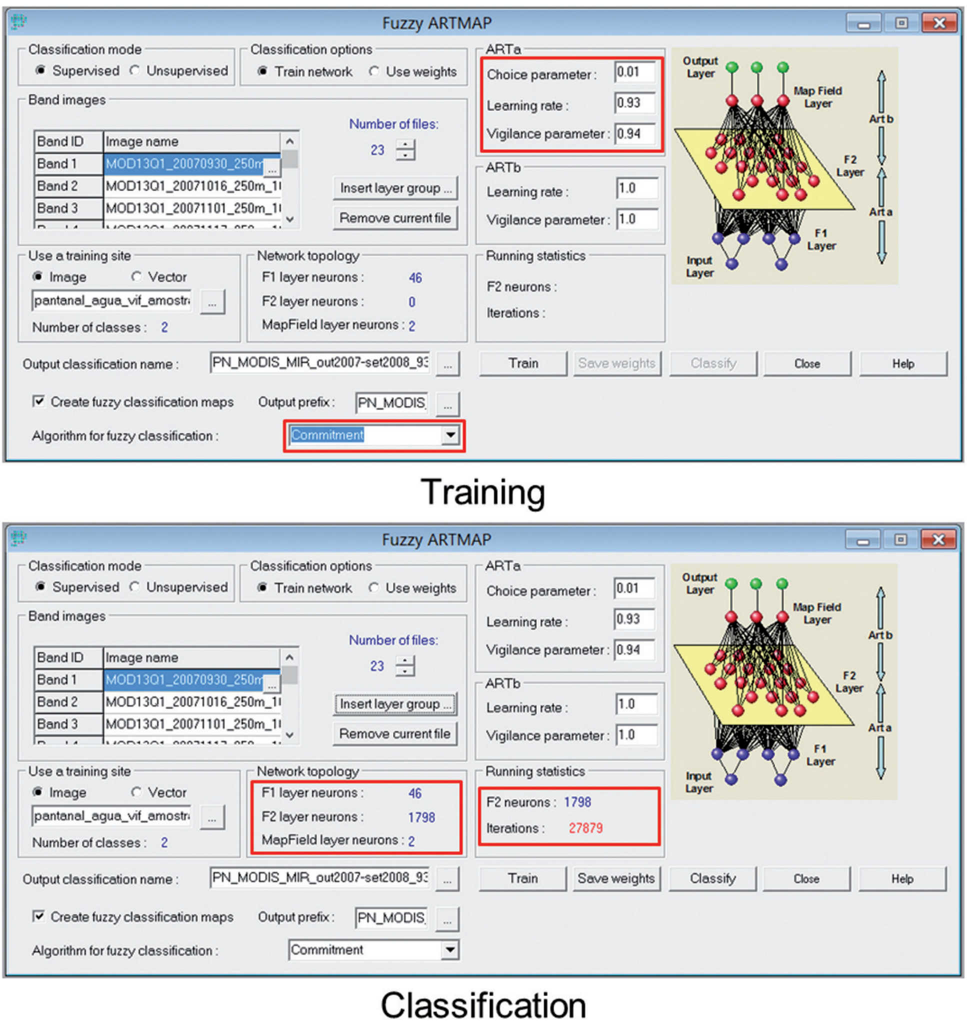

Figure 5 - Fuzzy ARTMAP interface from IDRISI

The Fuzzy ARTMAP training phase was done quickly, in approximately two minutes. This very short time is related to the use of the fuzzy intersection operator, which is a generalization to improve the performance of the network, referring mainly to the time for the execution of the training.

Referring to the network topology, layer F1 contains the double of neurons from the size of the input variables, to preserve the size of information, in this case 2 x 23 input variables equivalent to 46. The number of neurons of layer F2 grows dynamically during the training process, and it is directly related to the parameterization of ART_a. The higher the training rate, the more neurons at layer F2 and more information of new patterns are incorporated to the network. The higher the vigilance parameter, the more neurons are generated at layer F2, which produces images with more homogeneous pixels, with higher values of CMT. The chosen parameter determines the winner of the output class for a certain pixel, and it is subject to the resonance test based on the vigilance parameter. The classification phase was slower due to the dimensions of the input variables, taking around two hours of processing time.

Figure 6 presents CMT images of class Water, resulting from classification of Fuzzy ARTMAP, for the hydrologic years 2007/2008 and 2008/2009 at the Pantanal. The variation gradient of the colors in blue to cyan tones, green and yellow tones, represents the transition from class Water, with high proportions of water in the pixels, to the class Non-Water, which was not inundated.

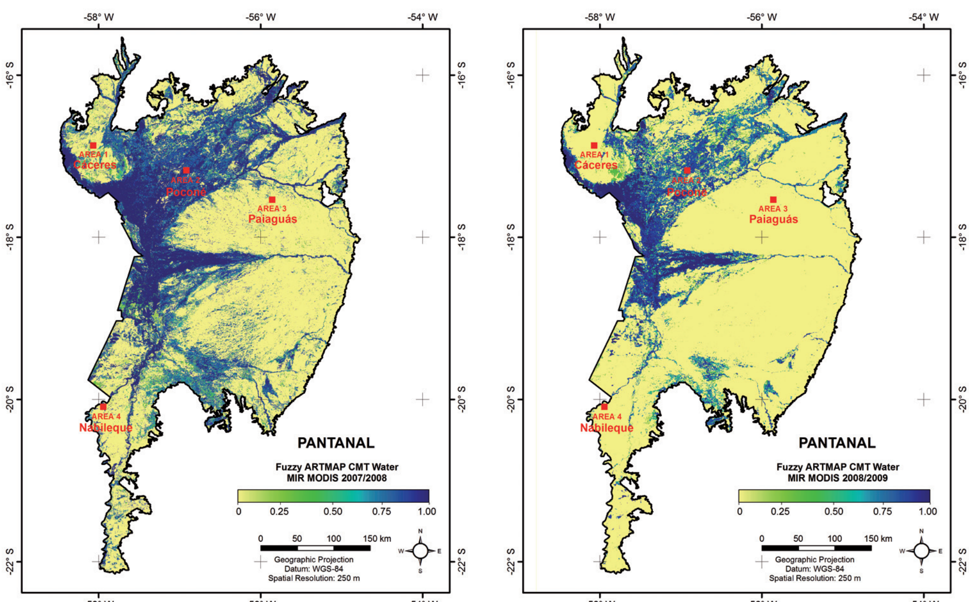

Figure 6 - CMT Water images for the hydrologic years 2007/2008 and 2008/2009

A visual analysis of figure 6 shows that the proportions of class Water during the hydrologic year 2007/2008, flood pronounced, are distinctly higher than during the hydrologic year 2008/2009, strongly dry, confirming the characterization of the hydrologic cycle, carried out with hydrometric data of Paraguai river, collected in Ladário.

For the validation of CMT Water model, generated by the Fuzzy ARTMAP classification, the analysis of the ROC curve was employed for the hydrologic years 2007/2008 and 2008/2009. To do this, the image with the CMT measures (Figure 6), which expresses the degree of commitment of pixels with class Water, was compared with the reference map (Figure 4), which shows the geographic localization of permanently inundated areas and those influenced by inundation.

Figure 7 presents the ROC curve, considering 100 similar thresholds to calculate the area under the curve (AUC) for the hydrologic years 2007/2008 and 2008/2009. Analyzing the ROC curve, it is possible to notice that with the increase of the cutoff threshold, the discriminating power of the CMT Water model also increases, keeping a good relation between the sensitivity and the specificity of the classifier, which allows a larger area under the curve, obtaining consequently a higher performance.

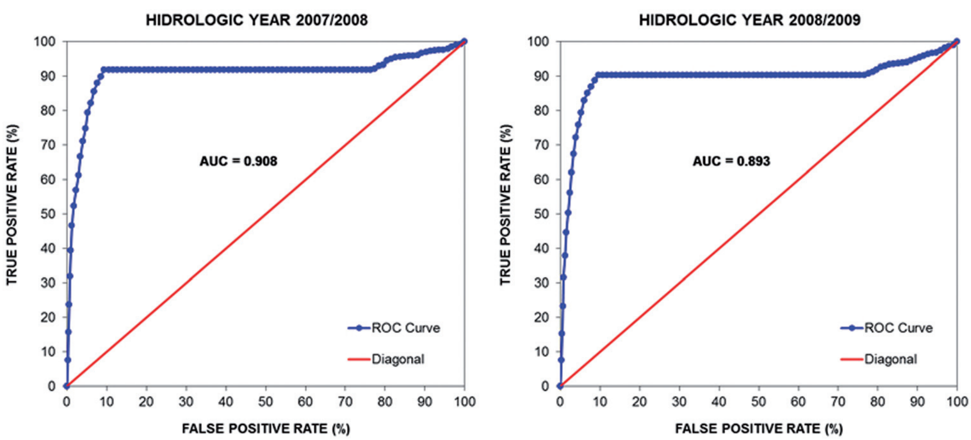

Figure 7 - ROC curves between the CMT Water classification models for the hydrologic years 2007/2008 and 2008/2009 with reference map

The AUC of CMT Water model classification was of 0.908 and 0.893 for the hydrologic years 2007/2008 and 2008/2009, respectively, which are high values, remarkably higher than the random models, in case the CMT measures had the tendency to be distributed randomly over the diagonal (AUC = 0.50) (PONTIUS; PARMENTIER, 2014). This fact demonstrates the excellent suitability of sub-pixel classification models, generated by the Fuzzy ARTMAP neural network, proving that it is really plausible to map inundated areas from the Pantanal based on the Commitment measure.

The quantification of the flooded areas was calculated by the multiplication of the area from the MODIS pixel times the sum of the CMT Water measures, considering the internal pixels from the vector borders of the Pantanal, using Equation 2. For the hydrologic year 2007/2008, the estimation of the flooded area from the Pantanal was of 52,226 km^2. For the hydrologic year 2008/2009 it was of 28,535 km^2, approximately 55% less than at the previous year.

When compared with the simple counting of pixels classified based on traditional methods, the Commitment measures have a tendency to present more reliable estimates, when considering that a pixel can be constituted by different portions of water and other cover types.

The field validation of studies from such a dynamic nature and at such a spatial size is very complex, and it depends strongly on local information, collected several times during the year, which are not available in this study. In this sense, a comparison of the results with those obtained by Padovani (2010) was made for the same hydrologic years, using a spectral mixture model which was also applied to the MODIS time-series data. The confrontation with the estimates presented here indicated the same tendency and magnitude with those found by the author, who quantified the flooded area with 52,894 km^2 for the hydrologic year 2007/2008 and around 22,000 km^2 for the hydrologic year 2008/2009.

Although the methods described presented different values for the hydrologic year 2008/2009, characterized by a strong drought, it must take into account that these results are estimates and not the real data of the flooded areas from the Pantanal. So it is not possible to state which of these values are the correct one, but the finding of convergence is clear among the inundation estimates of both studies, confirming the characterization of the hydrologic cycle, done with hydrometric data from the Paraguai river, collected in Ladário.

Therefore the Commitment measure of the Fuzzy ARTMAP classifier enabled the quantification of flooded areas, demonstrating the potential for the sub-pixel analysis of MODIS time-series data. These results may help those monitoring systems of inundations in the Pantanal.

CONCLUSIONS AND SUGGESTIONS

MIR MODIS data allowed monitoring of areas prone to flooding in the Pantanal, during hydrologic years 2007/2008 and 2008/2009.

The drought and flood period is quite variable in the entire Pantanal, occurring from North to South and from East to West.

The sub-pixel classification models, generated by the Fuzzy ARTMAP neural network, demonstrated an excellent suitability for the mapping and quantification of flooded areas of the Pantanal based on the Commitment measure.

The water proportions obtained from the Commitment measure, confirm the characterization of the hydrologic cycle done with hydrometric data from Paraguai river, collected in Ladário.

In future studies it is suggested to use reference field data, which would allow the selection of training samples of specific land use classes, aiming to improve the spectral variability among classes and to help in the learning process of pattern recognition.

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