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WATER BALANCE OF THE UPPER PARAGUAY BASIN AND ITS RELATIONSHIP WITH HYDROCLIMATOLOGICAL DYNAMICS OF THE PANTANAL WETLAND

BALANÇO HÍDRICO DA BACIA DO ALTO PARAGUAI E SUA RELAÇÃO COM A DINÂMICA HIDROCLIMÁTICA DO PANTANAL

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ABSTRACT

Water storage in a drainage basin determines its water security. The quantity of water retained in the watershed can be measured by means of the water balance calculation. This balance can be defined by the input of water subtracted from the outputs. However, for the Pantanal, the measurements of water inlet and outlet are expensive, which makes the use of remote sensing data a high impact tool with clear socioeconomic advantages. Studies of water availability with orbital sensors are relatively scarce in the Upper Paraguay Basin (BAP). This work is an attempt to estimate the BAP water balance using rainfall and evapotranspiration remote sensing data from the Tropical Rainfall Measuring Mission (TRMM) and the MODIS Global Evapotranspiration Project (MOD16), respectively. The results indicate that BAP had an annual surplus of water between 2000 and 2014, though water parameters seem weakly correlated at annual basis. However, there may be atmospheric-climatic phenomena that maximize the correlation between the hydrological parameters and the temperature anomaly with delays of 2 to 5 years, suggesting lagged teleconnections with QBO and ENSO.

Keywords: image processing; Quasi Biennial Oscillation; El Niño – Southern Oscillation; MODIS; TRMM.

RESUMO

O armazenamento de água de uma bacia de drenagem determina a sua segurança hídrica. A quantidade de água retida na bacia pode ser medida por meio do cálculo do balanço hídrico, definido pelas entradas de água subtraída das saídas. As medidas hídricas de entrada e saída em uma bacia de drenagem são onerosas, o que torna o uso de dados de sensoriamento remoto uma ferramenta de grande impacto socioeconômico para fins de gestão. Somado a isto, tem-se que estudos de disponibilidade hídrica com sensores orbitais são relativamente escassos para a Bacia do Alto Paraguai (BAP). Dessa forma, a partir do processamento de dados de precipitação do Tropical Rainfall Measuring Mission (TRMM) e de evapotranspiração do MODIS Global Evapotranspiration Project (MOD16), o presente trabalho traz uma estimativa do balanço hídrico da BAP com sensores orbitais. Os resultados indicam que a BAP apresentou um superávit hídrico anual entre 2000 e 2014, muito embora os parâmetros hídricos anuais sejam pouco correlacionados. No entanto, parece haver fenômenos atmosféricos-climáticos que maximizam a correlação entre os parâmetros hidrológicos e a anomalia de temperatura com atrasos de 2 a 5 anos, presumivelmente via teleconexões climáticas defasadas com QBO e ENSO.

Palavras chave: processamento de imagens; Oscilação Quasi-Bienal; El Niño – Oscilação Sul; MODIS; TRMM.

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WATER BALANCE OF THE UPPER PARAGUAY BASIN AND ITS RELATIONSHIP WITH HYDROCLIMATOLOGICAL DYNAMICS OF THE PANTANAL WETLAND

1. INTRODUCTION

Large-scale spatial-temporal changes in water balance determine water security of hydrological basin. As diverse productive activities require the use of water resources (from agricultural activities and industrial processes, besides generation of electric energy – e.g. hydroelectric), ensuring and guaranteeing water are of paramount importance for the socioeconomic development of any society and, therefore, must be treated with attention.

The water balance in watersheds is defined by the relationship between water inflows subtracted from the water which left the system. The net balance is expressed by ΔS = P-ET-Qs [Eq.1], where ΔS is the net change in stored water volume; P is precipitation (Vinput); ET is evapotranspiration (Voutput); and Qs is the outflow from the basin (Houtput).

The measurement of large-scale terrestrial observation variables is costly in watersheds because of difficulties in both the access and maintenance of the equipment. As a result, orbital remote sensing data has become very useful and a reliable source of hydrological information on the Earth's surface. In addition, several drainage basins in Brazil have hydrological data limitations in situ, and most studies are whether conducted only in small areas or based on simplified approaches (GALDINO; CLARKE, 1997; NUNES *et al*., 2016; MACEDO *et al*., 2019). A recent paper considers the set of rainfall stations available to study long-term rainfall changes in the Pantanal (BERGIER *et al*., 2018).

In general, studies of the hydrology of the Upper Paraguay Basin (BAP) rely only on in situ measurements of gauge stations (precipitation, elevation and fluvial flow), and the Ladário gauge station is the main reference, since it has provided data of the level of the river from 1900 to the present day. Examples of such studies are those developed by Hamilton *et al*. (1996), Clarke *et al*. (2003), Prass *et al*. (2012) and Bergier (2013). In another study, the Linear Spectral Mixture Model (SHIMABUKURO *et al*., 1998) in MODIS vegetation index images was used in the study and quantification of the flood dynamics of the Pantanal (PADOVANI, 2010). Other authors have used numerical or process-based models to simulate flow and water flow paths throughout the BAP by means of interpolation of meteorological data (BRAVO *et al*., 2012; PAZ *et al*., 2014).

Despite all this research, to date, few studies have been carried out to obtain the BAP water balance using orbital data (e.g. PENATTI *et al*., 2015). In this perspective, the present paper presents new information for the understanding of the hydrological regime of the BAP, proposing a new method of estimating the water balance, which, in general, reflects the future state or hydrological condition of the entire Pantanal. In addition, the paper also provides an assessment of how hydrological parameters are related (through statistical analysis of linear regression), in order to better understand the hydrological dynamics of the basin as well as how it is affected by the characteristics of the Pantanal.

In addition to the basin water balance, the scope of this work is to provide a tool that allows calculations and estimates of precipitation and evapotranspiration at monthly and annual scales. The proposal is to perform the water balance (c.f. Eq.1) of the drainage basin of the Paraguay River with catchment area determined as a function of the gauge station of Porto Murtinho (Figure 1). Thus, the main objective of this work is to estimate the annual water balance of the drainage basin of the Paraguay River with outlet at the gauge station of Porto Murtinho. The secondary objective is to present a new methodology to estimate the water balance based on orbital data of precipitation and evapotranspiration in this river basin. In addition, the article also provides a new perspective on the hydrological dynamics of the BAP and how these dynamics are modulated by the geological and geomorphological aspects of the Pantanal.

2. MATERIALS AND METHODS

2.1. Study area

BAP has its outlet on the border between Brazil and Paraguay, with an area of approximately 600,000 square kilometers in

Bolivia, Paraguay and Brazil, with 362,376 km² in last one, of which 48% are in the state of Mato Grosso and 52% in the state of Mato Grosso do Sul (SILVA, 2010). The area of the basin delimited in this study is a little smaller, since it has its outlet upstream of the mouth of the river Apa: 583,798.25 km².

BAP has three distinct regions: the Plateau, the Pantanal and the Chaco (Figure 1). The Plateau is a high region with elevation higher than 200 m and can reach up to 1400 m of altitude. It has well defined and convergent drainage located in the eastern and northern portion of the BAP, almost entirely in Brazilian territory. The Pantanal is a lower region, located in the center of the basin, where rivers flood the plains and feed a complex distributary drainage system that includes thousands of lakes, divergent and multichannel streams (anabranching) and seasonal flood and drainage areas. The Chaco, an endorheic or indefinite drainage system that ends in marshes and lakes, is located on the western border of Brazil and has an annual rainfall of less than 1000 mm.

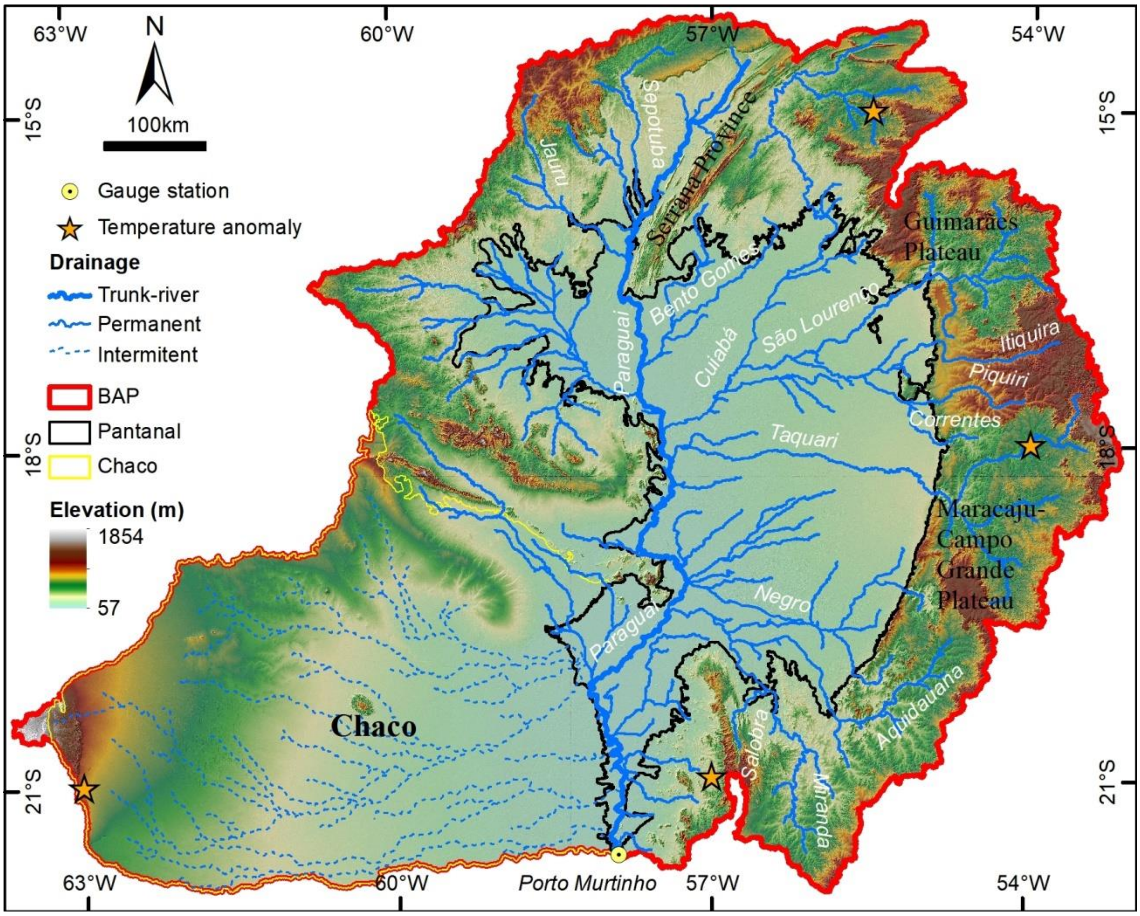

Figure 1 - Basin of drainage of the Paraguay river with outlet in the gauge station of Porto Murtinho. Drainage network and basin boundary obtained by means of an automatic method (ESRI, 2010). Elevation data: SRTM 90m. Limits of the Pantanal according to Padovani (2010). Temperature anomalies obtained in NOAA (2018). Cylindrical projection, datum WGS-84.

The predominant climate of the basin according to the Köppen classification is AW – tropical humid type, with average annual temperatures around 25°C. In the months of September to December temperatures can exceed 40°C. Between May and July, the temperature declines dramatically, due to the entry of cold air mass coming from the south. The mean annual precipitation of BAP varies between approximately 800 mm in some regions of Brazil's border with Bolivia (Chaco) and almost 2000 mm in some regions in the north of the basin (CLARKE *et al.*, 2003). Rainfall occurs mainly in the summer months, with winters being generally dry. Most annual rains occur from November to March, whereas from April to September is the driest period (MARENGO *et al.*, 2015). Important feature of the basin is the strong precipitation gradient that exists north-south and east-west (*ASSINE et al*., 2015).

In the Pantanal, during flood periods, water flows from the rivers to the plains because the downstream sections have a lower flow capacity than the upstream sections (TUCCI; GENZ, 1997). The morphology of the Pantanal is composed of a great number of depressions, which when water-filled, form a landscape of small lakes, which interconnect themselves in the high waters, damming them after the level of the rivers are lower. Therefore, much of the upstream water is retained on the plain, transforming the region into an immense reservoir.

Within the Brazilian territory, the main tributaries of the Pantanal are the Cuiabá, São Lourenço, Taquari, Aquidauana and Miranda rivers. The flow occurs from the Plateau to the Pantanal, where the rivers suffer a drastic reduction of speed due to the abrupt change of slope when entering the Pantanal, and associated with this occurs the deposition of the sediments, the sedimentation of the beds and loss of the erosive power that is translated by a smaller cross section than that of the upstream reach.

The alluvial plains that make up the Pantanal therefore work as a large reservoir that retains most of the water from the Plateau, thus regulating the flow of the Paraguay River and its tributaries into the Pantanal. Due to the geomorphological (topographic gradient) and sedimentary characteristics of the Pantanal, the flood pulse phenomenon occurs, which corresponds to the lag of the flow peak registered from upstream to downstream. The flood pulse occurs in canal-plain systems and was first described by Junk *et al*. (1989). From the ecological point of view, the flood pulse is the main force of control and configuration of the biota in a canal-plain system (JUNK *et al*., 1989). This phenomenon, characteristic of fluvial systems with flood plain, was documented in the Pantanal in the study carried out by Padovani (2010), in which the flooded areas were mapped in a time series of the year 2006. Interestingly, even at the end of the cycle, a good amount of water still remains in the plain, indicating that the waters that enter the system in a given year affect the water balance in the following year.

During the period when the rivers remain in their bed-stream, and there are no precipitations, the volume of water retained in the plain decreases under the effect of evapotranspiration and the infiltration that supplies the water table. This characteristic shows in brief the water balance of the Pantanal in the periods of drought, which may be the cause of the decreasing flow rate downstream, detected in some points of the Pantanal, such as that occurring in the Cuiabá river (TUCCI; GENZ, 1997). However, the great amount of water that remains in the plain is clear, even in the dry times, a fact that influences the flood of the following years.

2.2. Dataset and processing

The present work estimates the water balance of the Paraguay river basin above the gauge station of Porto Murtinho using data from precipitation (Vinput), evapotranspiration (Voutput) and fluvial discharge (Houtput). Tropical Rainfall Measuring Mission (TRMM) rainfall data, with 0.25° spatial resolution, were used to compute Vinput (HUFFMAN *et al*, 2007). Precipitation was estimated using the TRMM-3B43 product, which presents values of monthly precipitation rate. Precipitation rate data of 3B43 product were converted to accumulated precipitation (in km³) by means of expression $P_{Acc} = (P_{tx} \times D \times 24 \div 1 \times 10^{6}) \times A$ [Eq.2], in which P_{Acc} is the accumulated precipitation in cubic kilometers (km³); P_{tx} is the precipitation rate given by 3B43 product; D is the number of days in the month to be calculated; A is the area of each pixel of the 3B43 product (cell size in X multiplied by cell size in Y).

Evapotranspiration in the basin was estimated using MOD16A2 data from Numerical Terradynamic Simulation Group – NTSG (MU *et al.*, 2007; MU *et al*., 2011; MU *et al.*, 2013). The MOD16A2 (0.05° spatial resolution) products of the NTSG were converted into km³ for each month in each year. The values of the pixels were then integrated to obtain the annual evapotranspiration of the basin. To successfully perform BAP water balance calculations, a tool (model) was developed through ArcGIS ModelBuilder 10 (ESRI, 2010). This tool is available for use in other regions of the world (see Complementary Material). The **Erro! Fonte de referência não encontrada.** and **Erro! Fonte de referência não encontrada.** present a simplification of the flowchart of the tools and the integrations of the data that provide the annual precipitation and evapotranspiration maps. The evapotranspiration data provided by the NTSG have null values equal to 32767. In this way, these data were first processed to eliminate pixels with the values quoted. Therefore, it is recommended that if the original NTSG files are used, they are processed to eliminate null-value pixels (32767). An alternative is to use the files provided in the complementary material (section 7).

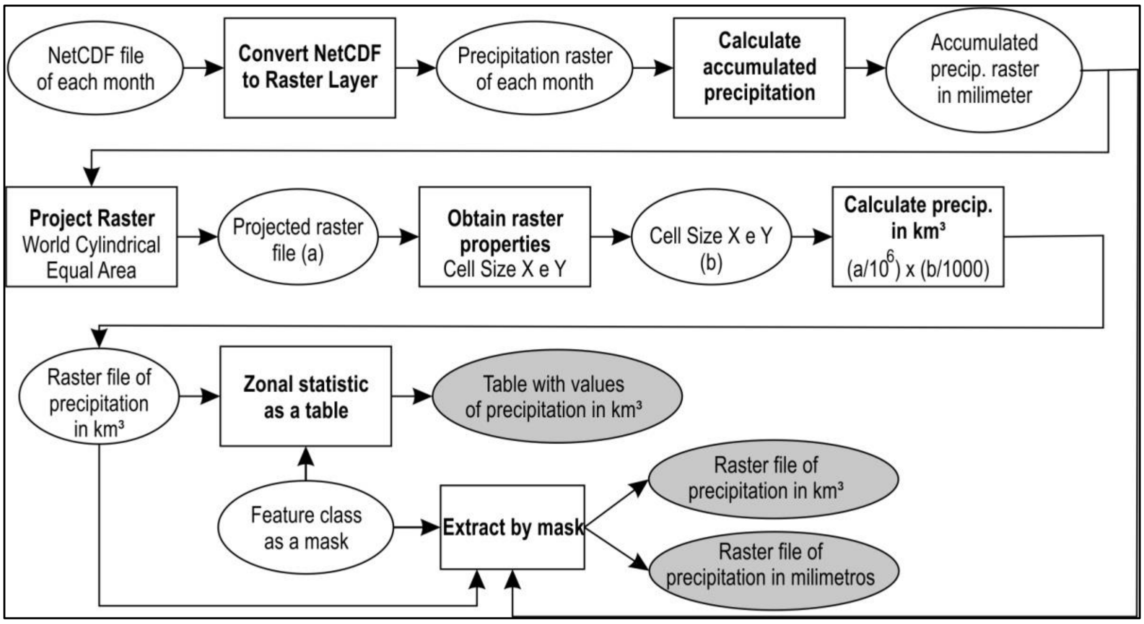

Figure 2 - Flowchart of the model for calculation of annual precipitation. The rectangles indicate processes and the ellipses products. Dark ellipses mean output parameters.

In addition to annual precipitation and evapotranspiration, the monthly values of these two hydrological parameters were also calculated. For this task, a tool was also created using Model Builder. This tool calculates the monthly precipitation and evapotranspiration (Jan-Dec) in millimeters and makes a statistical analysis (minimum, maximum and average values) of the area considered (in this case, the BAP). Thus, it was possible to calculate monthly rainfall and evapotranspiration, in cubic kilometers (km³), between 2000 and 2014, converting the values in millimeters to kilometers and multiplying by the value of the area of the basin in square kilometers (583,798.25 km²).

The hydrological parameters were converted into cubic kilometers to allow comparison with the discharge values of the basin, which has its measurement in volume values per unit time (m³/s). Therefore, the values of the water balance presented should be understood as the volume of water entering or leaving the basin over a year (km³/year), thus equalizing all hydrological parameters for the same unit of measurement.

The river discharge of the basin (Houtput) was determined using the flow data of the Porto Murtinho station, calculated by the rating-curve available on the website of the National Water Agency (ANA, 2018). Average monthly discharges were constructed from calculated discharges at the station. The total volume of water output from the basin was calculated as equivalent to the area below the monthly average flow. The months were transformed into seconds and the area was calculated by the Gauss matrix method: $Houtput = Area = Volume\ (m^3) = {}^{1}/_{2}\,|x_1y_2 + x_2y_3 + \cdots + x_{n-1}y_n + x_ny_1 - x_2y_1 - x_3y_2 - \cdots - x_ny_{n-1} - x_1y_n|$ [Eq.3]; where x is the month expressed in seconds and y is the flow expressed in m³/s. For this task, a tool was also created and made available in complementary materials (section 7).

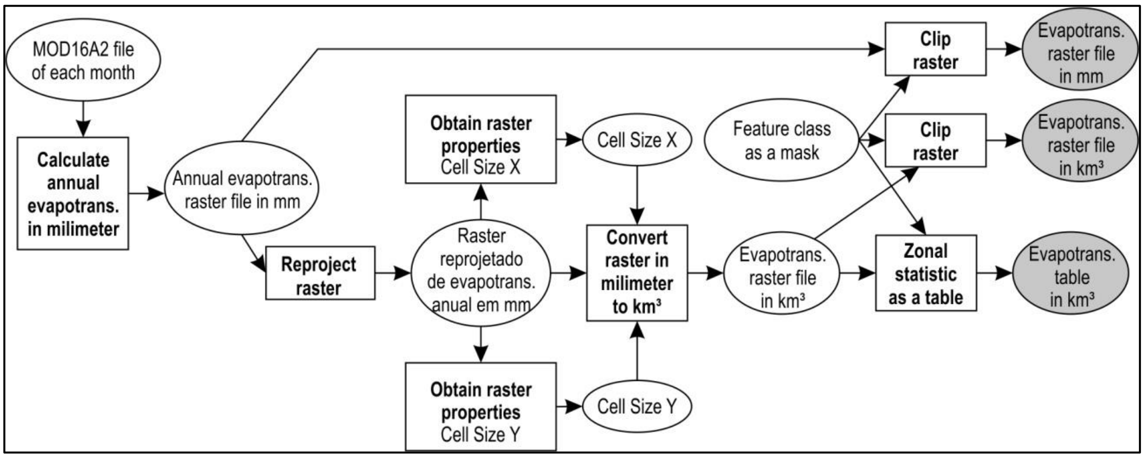

Figure 3 - Flowchart of the model for calculation of annual evapotranspiration. The rectangles indicate processes and the ellipses products. Dark ellipses mean output parameters.

The values obtained (P, ET and Qs), both monthly and annual, were later submitted to statistical analysis (linear regression) to understand the relationship between the hydrological parameters of BAP. In order to analyze the relationship between the hydrological parameters, the linear correlation coefficient (r) and the standard error of the estimation were used to evaluate how the variables (P, ET and Qs) relate themselves and if it is possible to estimate one (dependent variable) as a function of the other (independent variable). Regression analyzes were performed using the Microsoft Excel© Data Analysis tool.

3. RESULTS AND DISCUSSION

The values of precipitation, evapotranspiration, discharge and annual water balance for the fifteen years measured between 2000 and 2014 are presented in Table 1 e Figure 4. The spatial distributions of annual precipitation are shown in Figure 5. The spatial distributions of annual evapotranspiration are shown in Figure 6.

According to the values presented in Table 1, the interannual variation range of BAP precipitation was 282.5 km³ (maximum in 2014: 874.6 km³ and minimum in 2002: 592.1 km³). The mean annual precipitation in the BAP in the period was 730 km³ (~1250 mm) with standard deviation (σ) of 70.4 km³. The interannual variation in evapotranspiration was 279.1 km³ (maximum in 2014: 515.2 km³ and minimum in

2002: 236.1 km³). The mean annual evapotranspiration at BAP was 381.8 km³ (~ 654 mm) with σ equal to 105.1 km³. On the other hand, the interannual variation of the discharge of the basin was 40.8 km³ (maximum in 2014: 89.3 km³ and minimum in 2009: 48.5 km³). The mean annual discharge was 66.2 km³ (~ 2099 m³/s) with σ equal to 11.9 km³. On average, annual evapotranspiration was 48% lower than annual precipitation and annual discharge was 91% and 81% lower than precipitation and evapotranspiration, respectively.

Year	Precipitation (km³)	Evapotranspiration (km³)	Discharge (km³)	Water Balance (km³)
2000	721.9	274.0	63.1	384.8
2001	753.8	297.5	53.1	403.1
2002	592.1	236.1	68.4	287.6
2003	784.3	305.0	67.6	411.7
2004	740.1	260.1	63.1	417.0
2005	718.5	254.8	54.5	409.2
2006	783.6	323.2	73.8	386.7
2007	685.1	397.6	72.7	214.7
2008	711.7	457.5	75.4	178.8
2009	751.1	489.1	48.5	213.5
2010	597.2	478.0	64.6	54.6
2011	775.1	495.0	85.7	194.4
2012	742.7	493.8	51.4	197.4
2013	720.2	449.8	62.0	208.4
2014	874.7	515.2	89.3	270.2

Table 1 - Annual values of precipitation, evapotranspiration, liquid discharge and water balance of BAP.

In the fifteen years analyzed, the BAP water balance was always positive, indicating that the basin presented a water surplus, even in the driest years, as in the case of 2010 (Table 1). The BAP water balance remained relatively constant (~400 km³, Figure 4) in the first seven years analyzed (with the exception of 2002). From 2007, the basin had a reduction in its water storage, reaching the lowest value in 2010. The following year, the storage capacity increased to ~200 km³, maintaining it for two consecutive years and growing a bit in 2014 (~270 km³, Figure 4).

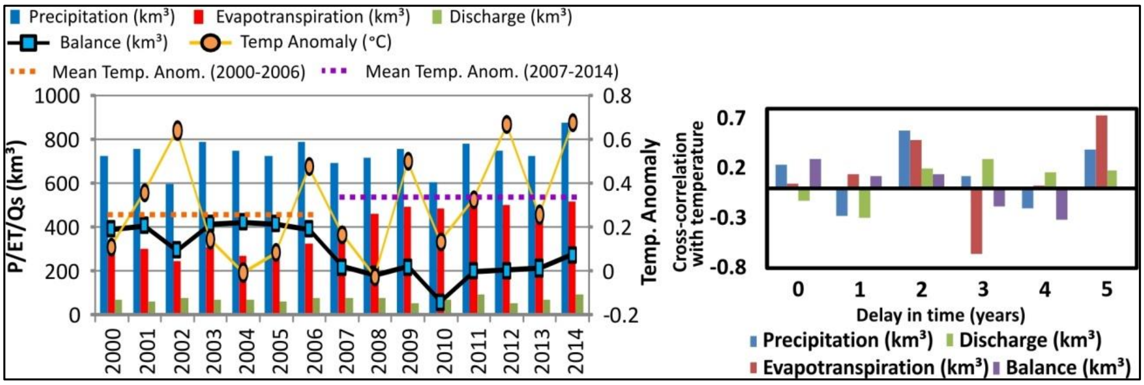

Figure 4 - Parameters of BAP water balance compared to temperature variations. Temperature anomaly data obtained at https://www.ncdc.noaa.gov/cag/global/time-series. For the location of the measured points, see Figure 1.

The decrease in BAP storage can be mainly explained by the increase in annual evapotranspiration from 2006/2007. An increase in ET was also verified by Penatti et al. (2015), as of November 2006.

Some years of the analyzed series presented particularities. In 2002, for example, annual ET was lower than in previous years, but precipitation was much lower, with a reasonably high discharge. The year 2010 was particularly dry, probably due to the low rainfall rate and, mainly, the high annual ET rate. BAP recovers its water storage from 2011 onwards by raising precipitation rates, despite the increase in the annual evapotranspiration rate. According to Figure 4, the increase in annual ET is not significantly correlated with the increase in temperature anomaly (TA) in the basin (r = 0.290; n = 15). However, the average TA in the period 2007 to 2014 was 0.08°C higher compared to 2000-2006 (Figura 4), suggesting a possible lagged connection between the increase in temperature and ET.

In addition, the cross-correlation (lag) analysis between TA and the other water parameters suggests that the correlations are maximized with time delays of 2 and 5 years of temperature (especially for P and ET, see Figure 4). This result may suggest the occurrence of teleconnections between Pantanal hydrology with climatological phenomena such as Quasi Biennial Oscillation (QBO) and El Niño Southern Oscillation (ENSO), respectively (YUAN et al., 2014). However, additional studies, preferably with longer data series, will be necessary to evaluate this hypothesis.

Other information that can be extracted from the precipitation maps (Figure 5) is the well-known rainfalls pattern in the basin, where these are larger in the plateaus and smaller in the Pantanal and Chaco. This irregular distribution of rain throughout the BAP is strongly influenced by differences in regional relief that create a type of orographic effect (VALERIANO et al., 2012; BERGIER, 2013) also known as "Fohn or Foehn winds" (ELVIDGE; RENFREW, 2016).

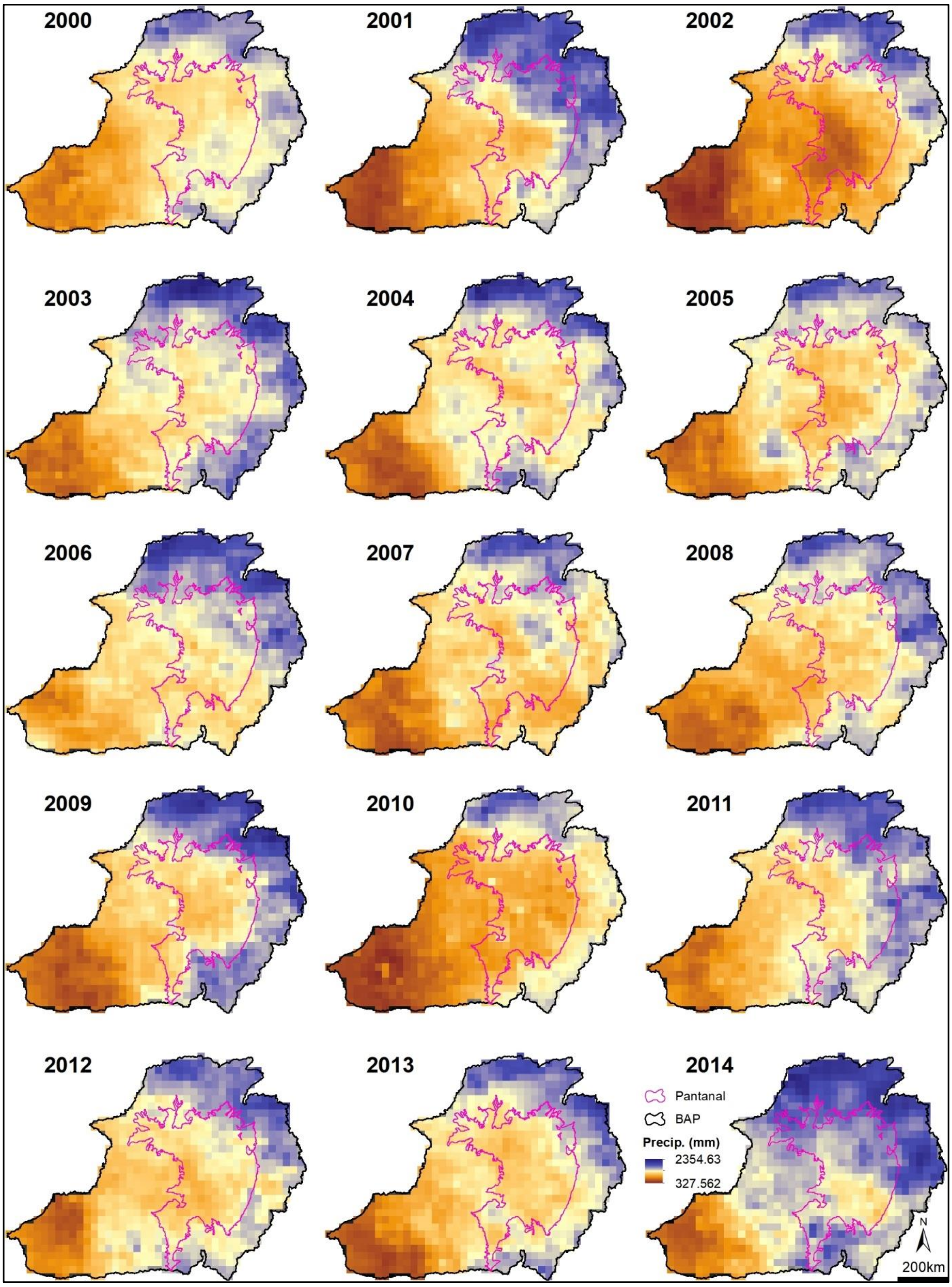

Figure 5 - Espacialization of the annual precipitation in the BAP (in millimeters) between 2000 and 2014 from the TRMM data.

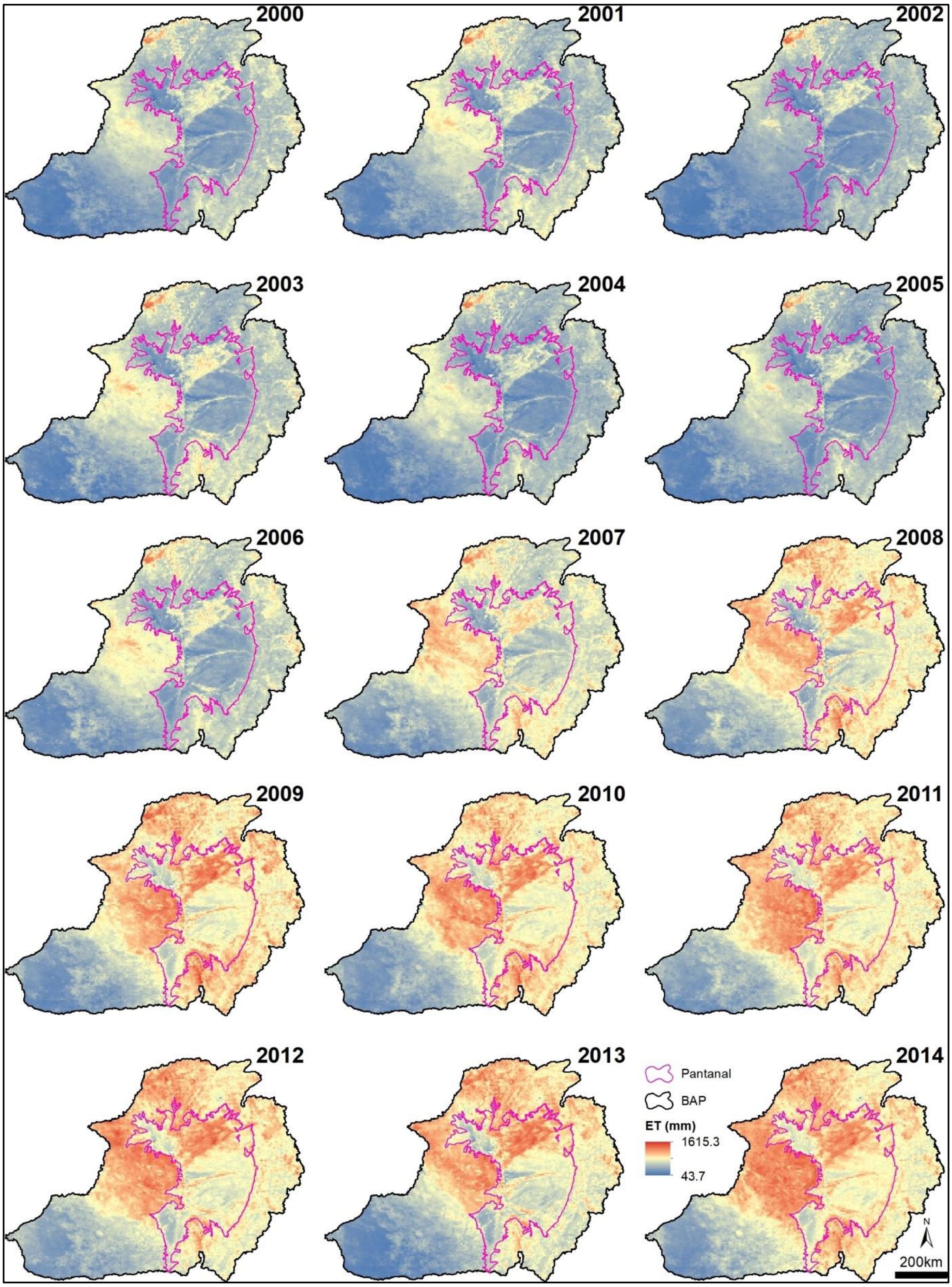

Figure 6 - Espacialization of annual evapotranspiration in BAP (in millimeters) between 2000 and 2014 from MOD16A2 data.

For the whole BAP, although the annual evapotranspiration presents low correlation with the annual precipitation (r = 0.236; n = 15), the spatial distribution maps of these two parameters (Figures 5 e 6) show that there is a general tendency for the first to be larger in regions where precipitation is larger and vice-versa. For example, the Chaco region has the lowest annual rates of precipitation and evapotranspiration. The correlation between these two BAP water parameters has already been demonstrated in the work done by Penatti et al. (2015), in which monthly, rather than yearly, values were analyzed.

Although the difference in resolution between the TRMM-3B43 and MOD16A2 products, this difference does not interfere in the correlation analyzes between the hydrological parameters used in this study, since tests revealed that the annual evapotranspiration values calculated for spatial resolution of 0.25° did not show a significant difference (-2.4 km³ on average, equivalent to -0.7%) in relation to the values calculated for resolution of 0.05°. Therefore, the values of ET and P are relative to the original spatial resolutions of their respective products and this does not entail major changes in the annual evapotranspiration values.

In the present work, pixel to pixel analysis was also performed, which shows a relative spatial correlation between precipitation and evapotranspiration in BAP (Figure 7). In this analysis, it was verified that evapotranspiration presents a moderate correlation with precipitation (r = 0.438; n = 11.955) in which P increases as long as ET increase (direct relationship), confirming what was observed in annual precipitation and evapotranspiration maps (Figures 5 e 6). Of the three areas that make up the BAP, the Chaco has the highest correlation between the two hydrological parameters (r = 0.593, n = 3.450). The Pantanal (r = 0.154, n = 3015) and the Plateau (r = 0.007, n = 5.490) have low correlation.

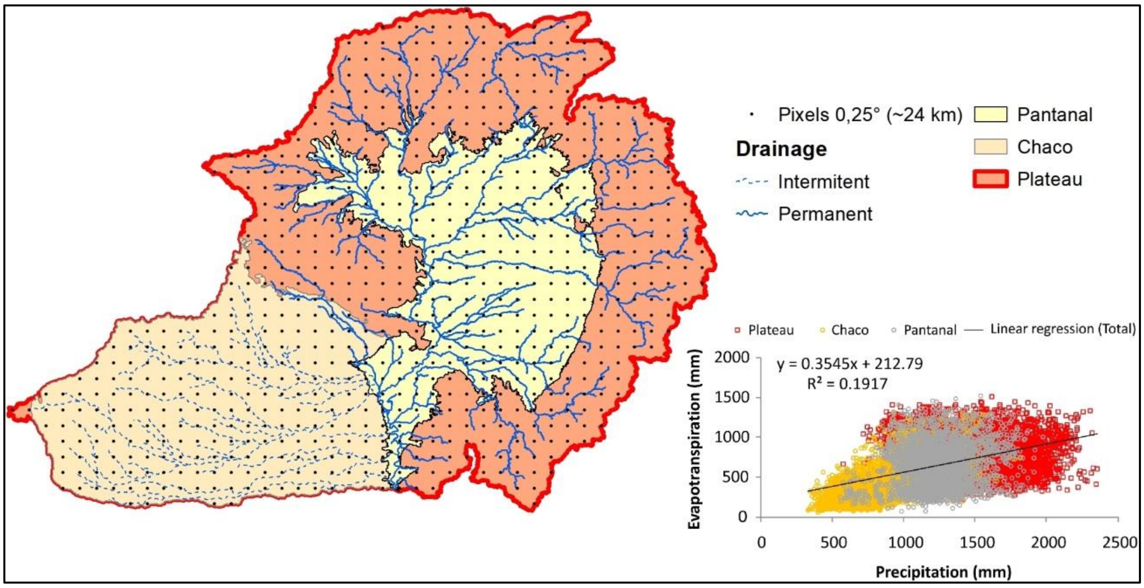

Figure 7 - Pixel to pixel analysis of the correlation between annual precipitation and evapotranspiration (2000 to 2014).

The correlation between precipitation and evapotranspiration was also verified with monthly rather than annual values and it was found that evapotranspiration correlates well with precipitation (r = 0.715; n = 180) in the fifteen analyzed years, with a direct relation (Figure 8A). Linear regression analysis also showed that monthly BAP evapotranspiration can be calculated by means of monthly precipitation, but this procedure leads to a standard error of ± 13,731 km³ (Figure 8A), which makes the use of precipitation unfeasible as a reference value to estimate evapotranspiration, since this error would give this estimate a very great uncertainty.

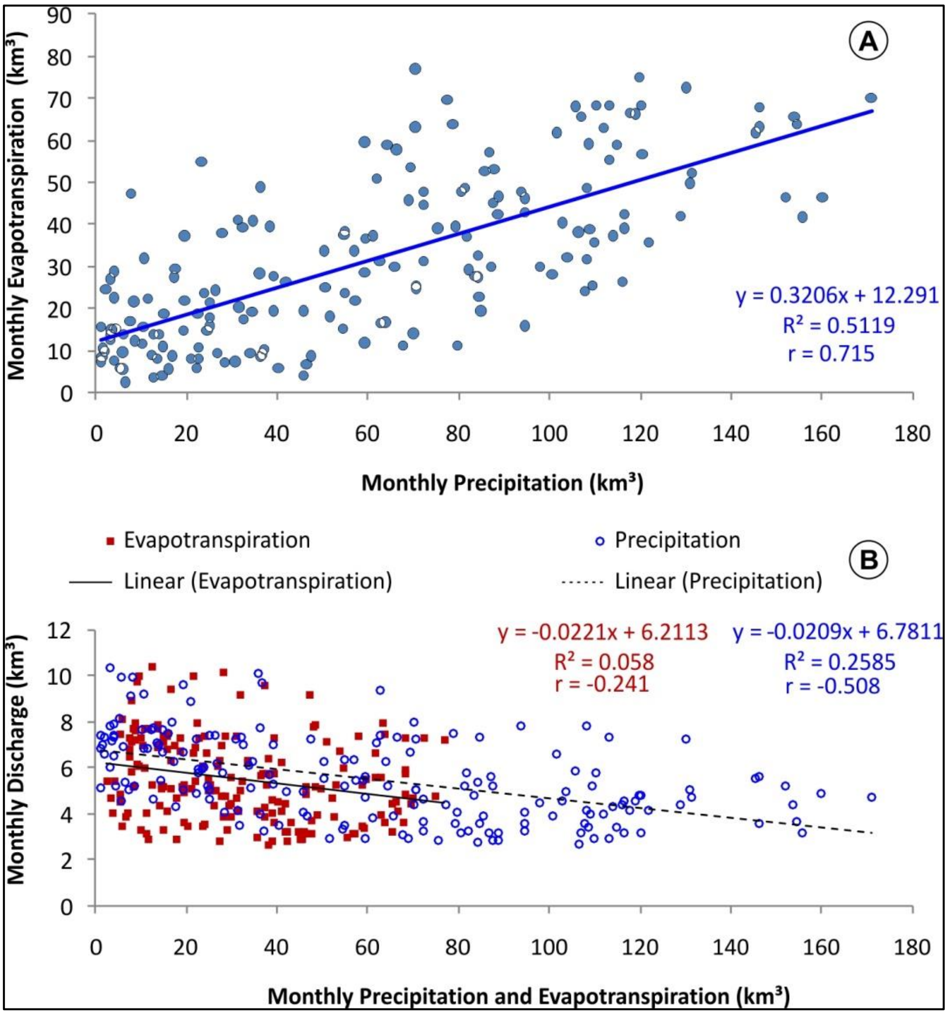

Figure 8 - Correlation between precipitation, evapotranspiration and discharge in BAP. A) correlation between monthly precipitation and evapotranspiration.. B) correlation between monthly precipitation/evapotranspiration and monthly discharge in BAP

The monthly discharge was also analyzed and it was verified that this one has an inverse relationship with both monthly precipitation and evapotranspiration (Figure 8B). In addition, the correlation between monthly discharge and monthly precipitation can be considered moderate (r = -0.508; n = 180), but the same cannot be said for monthly evapotranspiration (r = -0.241; n = 180). The inverse counter-intuitive relationship between precipitation and discharge must be triggered by the flood pulse of the Pantanal, which delays the flow along the Paraguay River. This phenomenon, already described in several other works in the Pantanal (e.g. ASSINE et al., 2015; CLARKE et al., 2003; TUCCI; GENZ, 1997), causes the delay of the flood peak, in which the highest discharge rates in the Paraguay River occur lagged with the rainy period throughout the basin. Thus, the months with the highest discharge value (July/August) are also the months of the lowest monthly rainfall. In the case of evapotranspiration, the inverse relationship with the discharge occurs mainly because the period of greatest discharge occurs in the months of lower temperatures (winter), which leads to lower rates of evapotranspiration.

Although the weak correlation, the monthly discharge can be estimated from the monthly precipitation or evapotranspiration, however, with standard errors of ± 1.55 and ± 1.75 cubic kilometers, respectively (Figure 8B). At first glance, these errors may seem insignificant, but it is important to remember that the low correlation coefficient makes the estimation of the discharge unfeasible through monthly precipitation or evapotranspiration.

4. CONCLUSIONS

The present work shows that the BAP is a drainage basin that presents a water surplus. The models developed using the ArcGIS 10 ModelBuilder (TRMM Annual Evapotranspiration; TRMM Monthly Precipitation; MOD16A2 Monthly Evapotranspiration) allowed to optimize the estimation of BAP both monthly and annual precipitation and evapotranspiration. With these tools it is possible to calculate the monthly and annual precipitation and evapotranspiration of the BAP and other regions of the earth visited by these orbital sensors. The optimization in the calculations is mainly due to automation in several stages of assimilation of the TRMM and MODIS data, reducing the chance of errors as well as the time needed to generate the products.

The annual precipitation values did not present a good correlation with annual evapotranspiration values, perhaps due to the low number of years measured (2000 to 2014). Another important finding is that annual discharge values from the basin also do not correlate well with the other two parameters measured. Precipitation and evapotranspiration in BAP have a good correlation when analyzed monthly. However, when compared to the monthly discharge, monthly precipitation and evapotranspiration presented a moderate and low correlation, respectively. The correlation between precipitation and discharge reflects the flood pulse dynamics of the Pantanal. The evapotranspiration has its relation with the discharge associated with the climatological dynamics of the BAP and the flood pulse of the Pantanal.

The water balance values show that there is a general tendency to decrease the amount of water stored in the BAP in the evaluated time interval. This trend can result from the increase in annual evapotranspiration in the basin, which from 2007 reached values close to 400 km^3/year. It was not possible to determine exactly the cause for the increase in evapotranspiration in BAP from 2007, even when considering changes in the basin temperature anomaly. However, cross-correlation analysis suggests that both this parameter and precipitation show higher correlations with temperature for lags of 2 to 5 years, possibly due to climatic-atmospheric phenomena such as QBO and ENSO, respectively, which should be addressed and evaluated in future studies.

5. ACKNOWLEDGMENT

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6. COMPLEMENTARY MATERIAL

The tool for calculating monthly and annual precipitation and evapotranspiration is available at http://twixar.me/C0FK. The tool for calculating the monthly and annual discharge in the basin is available at http://twixar.me/c0FK. The MOD16A2 files are available at http://twixar.me/3DFK. TRMM files are available at http://twixar.me/KDFK. A tutorial for using the tool is available at http://twixar.me/1DFK.

7. REFERENCES

ANA. **Sistema de Informação Hidrológica**. 2018. Disponível em: www.hidroweb.ana.gov. Acesso em 01/06/2018.

ASSINE, M. L.; MACEDO, H. A.; STEVAUX, J. C.; BERGIER, I.; PADOVANI, C.; SILVA, A. Avulsive Rivers in the Hydrology of the Pantanal Wetland. In: BERGIER, I.; ASSINE, M. L. (Ed.), **Dynamics of the Pantanal Wetland in South America** – The Handbook of Environmental Chemistry, v. 37. Berlin, Heidelberg: Springer, 2015. 4, p. 83-110. DOI: 10.1007/698_2015_35.

BERGIER, I. Effects of highland land-use over lowlands of the Brazilian Pantanal. **Science of The Total Environment**, v.463-464, p. 1060-1066, 2013. DOI: 10.1016/j.scitotenv.2013.06.036.

BERGIER, I.; ASSINE, M. L.; MCGLUE, M.; ALHO, C.; SILVA, A.; GUERREIRO, R. L.; CARVALHO, J.C. Amazon rainforest modulation of water security in the Pantanal wetland. **Science of The Total Environment**, v. 619-620, p. 1116-1125, 2018. DOI: 10.1016/j.scitotenv.2017.11.163.

BRAVO, J.; ALLASIA, D.; PAZ, A.; COLLISCHONN, W.; TUCCI, C. Coupled hydrologic–hydraulic modeling of the Upper Paraguay River Basin. **Journal of Hydrologic Engeneering**, v.17, p. 635-646, 2012. DOI: 10.1061/(ASCE)HE.1943-5584.0000494.

CLARKE, R. T.; TUCCI, C. E.; COLLISCHONN, W.. Variabilidade temporal no regime hidrológico da bacia do rio Paraguai. **Revista Brasileira de Recursos Hídricos**, p. 201-211, 2003.

ELVIDGE, A. D.; RENFREW, I. A. The causes of Foehn Warming in the lee of mountains. **Bulletin of the American Meteorological Society**, v. 97, n. 3, p. 455-466, 2016. DOI: 10.1175/BAMS-D-14-00194.1.

ESRI. Environmental Systems Research Institue. **ArcGIS 10**. Redlands, California, United States of America, 2010.

GALDINO, S.; CLARKE, R. T. **Probabilidade de ocorrência de cheia no Rio Paraguai, em Ladário, MS Pantanal**.Corumbá: EMBRAPA-CPAP, 1997.

HAMILTON, S. K.; SIPPEL, S. J.; MELACK, J. M. Inundation patterns in the Pantanal wetland of South America determined from passive microwave remote sensing. **Archiv fur Hydrobiologie**, v. 137, p. 1-23, 1996.

HUFFMAN, G. J.; ADLER, R. F.; BOLVIN, D. T.; GU, G.; NELKIN, E. J.; BOWMAN, K. P.; HONG, Y.; STOCKER, E.F.; WOLFF, D.B.. The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-Global, Multiyear, Combined-Sensor Precipitation Estimates at Fine Scales. **Journal of Hydrometeorology**, v. 8, p. 38-55, 2007. DOI: 10.1175/JHM560.1.

JUNK, W.J; BAYLEY, P.B.; SPARKS, R.E. The flood pulse concept in River-Floodplain systems. In: D.P. Dodge [ed.] PROCEEDINGS OF THE INTERNATIONAL LARGE RIVER SYNPOSIUM, v. 106, 1989, Can. Spec. Publ. Fish. Aquat. Sci., 1989, p. 110-127.

MACEDO, H.A.; STEVAUX, J.C.; SILVA, A.; MERINO, E.R.; LO, E.L.; ASSINE, M.L. Hydrosedimentology of the Paraguay River in the Corumbá fluvial reach, Pantanal wetland. **Revista Brasileira de Geomorfologia**, v. 20, n. 2, p. 255-271, 2019. DOI: 10.20502/rbg.v20i2.1500.

MARENGO, J.; SAMPAIO G.; ALVES, L. M. Climate change scenarios in the Pantanal. In: BERGIER, I.; ASSINE, M.L. (Ed.) **Dynamics of the Pantanal Wetlands in South America** – The Handbook of Environmental Chemistry, v. 37. Berlin, Heidelberg: Springer, 2015. 12, p. 227-238. DOI: 10.1007/698_2015_357.

MU, Q.; HEINSCH, F. A.; ZHAO, M.; RUNNING, S. W.. Development of a global evapotranspiration algorithm based on MODIS and global meteorology data. **Remote Sensing of Environment**, v.111, p. 519-536, 2007. DOI:10.1016/j.rse.2007.04.015.

MU, Q.; ZHAO, M.; Running, S. W.. Improvements to a MODIS global terrestrial evapotranspiration algorithm. **Remote Sensing of Environment**, v. 115, p. 1781-1800, 2011. DOI:10.1016/j.rse.2011.02.019.

MU, Q.; ZHAO, M.; RUNNING, S. W.. **MODIS Global Terrestrial Evapotranspiration (ET) Product (NASA MOD16A2/A3) - Algorithm Theoretical Basis Document: Collection 5**. Missoula: NASA Headquarters. 2013.

NOAA. **National Centers for Environmental information, Climate at a Glance**: Global Time Series, published May 2018, retrieved on June 13, 2018 from https://www.ncdc.noaa.gov/cag/

NUNES, M. C.; NEVES, S. A.; NEVES, R.; NERY, J. T. Comportamento da precipitação pluvial no município de Cáceres Pantanal Mato-Grossense no período de 1971 a 2011. **Científica**, v. 44, n. 3, p. 271-278, 2016.

PADOVANI, C. R. **Dinâmica das Inundações do Pantanal**. 2010. Tese (doutorado em Ecologia Aplicada) – USP/ESALQ, Piracicaba-SP.

PAZ, A. R.; COLLISCHONN, W.; BRAVO, J. M.; BATES, P.; BAUGH, C.. The influence of vertical water balance on modelling Pantanal (Brazil) spatio-temporal inundation dynamics. **Hydrological Processes**, v. 28, p. 3539-3553, 2014. DOI: 10.1002/hyp.9897.

PENATTI, N. C.; ALMEIDA, T.S.R.; FERREIRA, L.G.; ARANTES, A.E.; COE, M.T.. Satellite-based hydrological dynamics of the world's largest continuous wetland. **Remote Sensing of Environment**, v. 170, p. 1-13, 2015. DOI: 10.1016/j.rse.2015.08.031.

PRASS, T. S.; BRAVO, J. M.; CLARKE, R. T.; COLLISCHONN, W.; LOPES, S. R.. Comparison of forecasts of mean monthly water level in the Paraguay River, Brazil, from two fractionally differenced models.**Water Resources Research**, v. 48, p. 1-13, 2012. DOI:10.1029/2011WR011358.

SHIMABUKURO, Y. E.; NOVO, E. M. L. M.; PONZONI, F. J. Índice de vegetação e modelo linear de mistura espectral no monitoramento da região do Pantanal. **Pesquisa Agropecuária Brasileira**, v. 33, p. 1729-1737, 1998. Disponível em: https://seer.sct.embrapa.br/index.php/pab/article/viewFile/5057/7206.

SILVA, A. **Geomorfologia do megaleque do rio Paraguai, Quaternário do Pantanal Mato-Grossense, Centro-Oeste do Brasil**. Tese (doutorado em Geociências e Meio Ambiente) – UNESP, Rio Claro-SP, 2010.

TUCCI, C. E.; GENZ, F. Caracterização hidrológica da BAP. In: UFRGS-IPH (Ed.), **Plano de Conservação da Bacia do Alto Paraguai-PCBAP**. Brasília: Ministério de Recursos Hídricos e da Amazônia Legal, 1997, p. 181-264.

VALERIANO, M. d.; SALVI, L. L.; ARAGÃO, J. R. Relações entre a distribuição da precipitação e o relevo da bacia do alto Paraguai. In: SIMPÓSIO DE GEOTECNOLOGIAS NO PANTANAL, 4., 2012, Bonito-MS. São José dos Campos-SP: Embrapa Informática Agropecuária/INPE, 2012. p. 289-298.

YUAN, W.; GELLER, M. A.; LOVE, P. T. ENSO influence on QBO modulations of the tropical tropopause. **Quarterly Journal of the Royal Meteorological Society**, v. 140, p. 1670-1676, 2014. DOI: 10.1002/qj.2247.