METHODOLOGY FOR ANALYSIS OF DISTRIBUTION AND CLASSIFICATION OF THE INTENSITY OF *DEQUADA* FISH KILL EVENTS IN THE PANTANAL WETLAND

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Abstract

Extensive fish mortality occurs occasionally in the Pantanal wetland and the phenomenon is called *dequada* by local inhabitants. The phenomenon originates by deterioration water quality in rivers and lakes, and the depletion of dissolved oxygen (DO) is the major indicator. Researches have shown that *dequada* occurs when DO reaches values lower than 3 mg/L. In addition, the duration of these low DO values determines the intensity of fish mortality. This paper presents a proposed classification of *dequada* event, using water quality data for Pantanal rivers surveyed by National Agency of Water (ANA). The proposed method has qualitative and quantitative bases and utilizes mean DO value and duration of these values, based on historical series of DO measurements. The results are compared to other studies of the *dequada* phenomenon, showing that the method is efficient to determine locales with higher probability of *dequada*. The Paraguay River has displayed highest *dequada* intensity. The rivers with narrower floodplains, such as Piquiri River, do not have *dequada* or the intensity is lower. The phenomenon is shown to be linked to basin hydrological conditions.

Keywords: *Dequada.* Oxygen depletion. Limnology. Water quality.

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Resumo

Metodologia para análise da distribuição e classificação da intensidade do fenômeno de mortandade de peixes no Pantanal

O fenômeno de mortandade de peixes no Pantanal é conhecido popularmente como dequada. O fenômeno é originado pela deterioração da qualidade da água dos rios e lagos, sendo a diminuição do oxigênio dissolvido (OD) o principal fator. Estudos mostram que a dequada ocorre quando os valores de OD são inferiores a 3 mg/L. Além disso, o tempo de permanência desses valores também é um fator responsável pela intensidade do fenômeno. O presente trabalho visa apresentar uma proposta de classificação da dequada, utilizando-se dados de qualidade da água dos rios do Pantanal, registrados pela Agência Nacional de Águas (ANA). O método proposto tem base quali-quantitativa e utiliza o valor médio de OD e o tempo de permanência desses valores, dentro de uma série histórica. Os resultados obtidos são comparados a outros estudos já realizados sobre o assunto, mostrando que o método é eficiente para determinar os locais com maior probabilidade de ocorrência do fenômeno, sendo o rio Paraguai o principal corpo d'água a sofrer dequada com grande intensidade. Os rios com planície de inundação estreita, como o Piquiri, não apresentam ocorrência do fenômeno ou a intensidade é fraca. O fenômeno mostrou-se intimamente ligado às condições hidrológicas da bacia.

Palavras-chave: Dequada. Depleção do oxigênio. Limnologia. Qualidade da água.

INTRODUCTION

The phenomenon of fish mortality recorded in the rivers and lakes, relatively close to the Paraguay River, is commonly called "dequada" or "diquada", or "decoada". This is a limnological, highly complex, and little studied phenomenon with serious biological and ecological implications. Studies in the literature on this subject show that correct understanding of this phenomenon, and apart from increasing our understanding of the hydro-biogeochemical processes in the Pantanal, they also provide information to enable an assessment of its environmental impact (CALHEIROS; FERREIRA, 1996; OLIVEIRA et al, 2013). According Calheiros and Ferreira (1996, p.7), limnological studies (studies of the physical, chemical and biological aspects of freshwater systems) aim at unveiling a comprehensive understanding of the operation and form of the organization of each aquatic environment under study; they explain the dynamics and interrelationships with the biota, for which the knowledge of both of the water and fish are necessary to ultimately produce good management actions.

Any alteration either in the water level of the system or the residence time of the water in the plains triggers a series of changes in the limnological characteristics of the water bodies due to the interaction between the aquatic and terrestrial environments. The duration and intensity of these changes are linked with the hydrological features of the Upper Paraguay River Basin (BAP), which in turn reveal the climatic and geomorphological characteristics of the basin. Some of the more visible changes include increasing or decreasing the water transparency, hydrogenic potential (pH), electrical conductivity and concentration of the dissolved gases (particularly oxygen and CO_2), nutrients and materials in suspension. All these alterations accelerate a natural deterioration of the water quality ("dequada"), which results in the death of the fish relative to the magnitude of the phenomenon (CALHEIROS; FERREIRA, 1996). It is significant to note that this phenomenon is provoked by natural factors of channel-plain systems, which occur in many other environments besides the Pantanal (RABOUILLE et al, 2008; BRINKMANN; SANTOS, 1973). They cause the waters to overflow the plain resulting in the death of the terrestrial vegetation which is decomposed and increases the CO_2 content of the water receding back to the rivers in the ebb phase. The waters thus deprived of dissolved oxygen (DO) but possessing an increased carbon dioxide (CO_2) load induces respiratory stress in the fish populations, resulting in their death. However, it is noteworthy that the *dequada* phenomenon can behave as a regulatory mechanism in the dynamics of the aquatic communities (CALHEIROS; FERREIRA, 1996), thus acting as a type of natural selection in these environments.

The literature contains a limited number of studies regarding the limnological features of the Pantanal wetland, mostly involving technical reports and event summaries (CALHEIROS et al, 1991; CALHEIROS et al, 1996; CALHEIROS; HAMILTON, 1998; Da SILVA, 1984; FERRAZ de LIMA; CONCEIÇÃO, 1977). The objective of the present study is to analyze the limnological characteristics of the rivers that constitute the Pantanal, in order to propose the method of classifying the intensity and distribution of the phenomenon of fish mortality that occurs in the water bodies of this important ecosystem in Brazil.

PHYSIOGRAPHIC FEATURES OF THE PANTANAL

From the geological and geomorphological perspective, the Pantanal is a huge depositional system produced by a drainage network in which the rivers change position over time (ASSINE, 2005). Presently, the system includes alluvial plains and fluvial megafans, where the most important among them is the alluvial plain of the Paraguay River, which extends from Cáceres, goes past Corumbá and ends in Porto Murtinho (Fig. 1). The most important fluvial megafans are the Paraguay, São Lourenço, Taquari and Nabileque rivers (Figure 1).

The hydrology of the Pantanal is characterized by floods and droughts related to the climatic and geomorphological features of the region. The Pantanal is located in the transition zone between the humid tropical climate of the north (Amazon) and the semi-arid subtropical regime of the south (Gran Chaco), in South America. The air flow within the Intertropical Convergence Zone or Equatorial Convergence Zone (ZCITE) is subjected to the cancellation of the opposite effects of the wind patterns of the easterlies (BALEK, 1983). The annual sun movement leads to ZCITE migration from north to southward and virce-versa, which affect the humid tropical climate. This is the reason that this area experiences a typical dry-humid climate in which precipitation becomes the primary climatic variable (GARCIA, 1984). The regional climate can be distinguished as a seasonal tropical regime - Aw (Köppen system), with a distinct dry season from May to September and a wet season between October and April. The average rainfall is 1,250 $mm.year^{-1}$ with temperatures ranging from 21.4ºC (July) to 27.4ºC (December) (JUNK et al, 2006). The extremely flat terrain with rivers flowing across very gentle slopes is one of the most distinctive features of the Pantanal. In fact this causes a reduced cross-sectional area compared with the stretches of the rivers of the Plateau, thus limiting the flow of the Pantanal rivers. These features trigger the major flood pulse phenomenon (JUNK et al, 1989) which is vital for the maintenance of this ecosystem. The flood pulse of the waters of the Pantanal rivers can be observed from the lag of the flood peaks recorded along the Paraguay River (Figure 2D). It takes about four months for the flood wave to flow throughout the entire Pantanal, from the entry point of the Paraguay River at Caceres-MT, until its exit south of the Corumbá-MS, in the location termed the Pantanal of Nabileque.

Apart from the flood pulse, the Pantanal hydrology is characterized by continuous water loss from channels toward floodplain. This loss is often associated with typical distributary characteristic of several rivers of the Pantanal (Taquari and São Lourenço rivers) or the existence of an unconfined plain as in the case of the Paraguay River (MACEDO et al, 2014). The water loss in the Pantanal rivers to the floodplain is observed from the hydrograph of the stations present along the course of these rivers (Figures 1 and 2). This water loss is an essential factor favoring the existence of the *dequada*, given the requirements of the plain inundation.

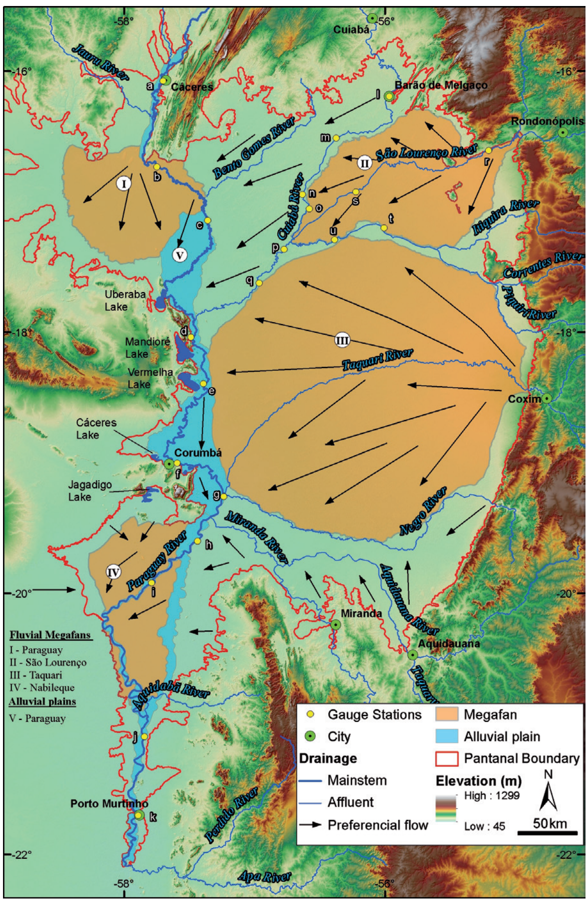

Figure 1 – Drainage network of the Pantanal wetland with Digital Elevation Model (DEM). Stations from which measurements are taken: a) Cáceres; b) Descalvados; c) Porto Conceição; d) Amolar; e) São Francisco; f) Ladário; g) Porto da Manga; h) Porto Esperança; i) Forte Coimbra; j) Barranco Branco; k) Porto Murtinho; l) Barão de Melgaço; m) Porto Cercado; n) São João; o) Ilha Camargo; p) Pousada Taimã; q) Porto do Alegre; r) Acima do Córrego Grande; s) São Jose do Boriréu; t) São Jerônimo; u) São José do Piquiri

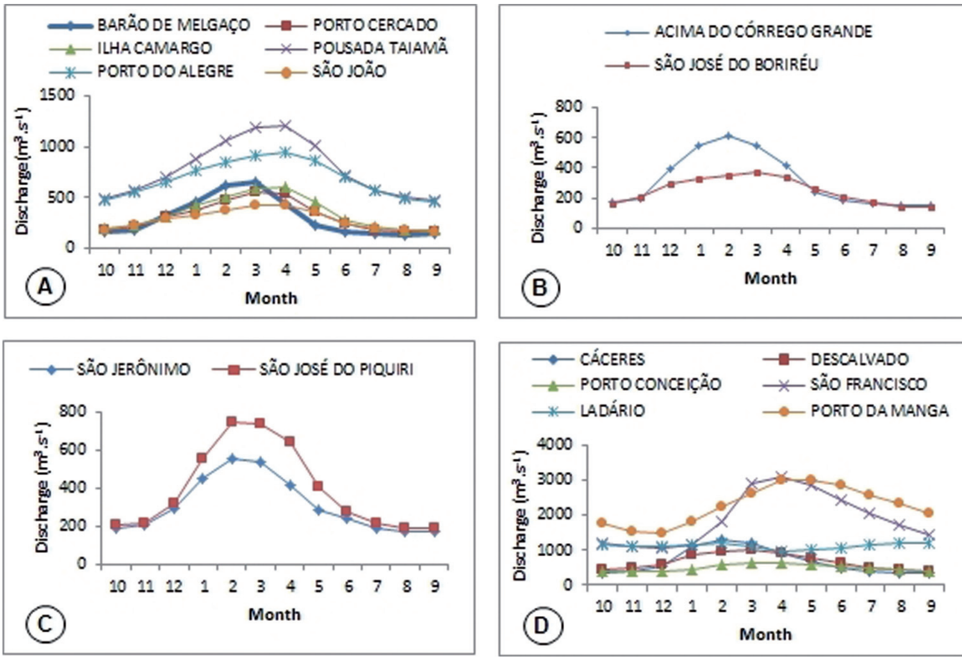

Figure 2 – Hydrographs of the main Pantanal rivers: A) Cuiabá River, B) São Lourenço River; C) Piquiri River; D) Paraguay River. Historical series of 1976-1981

MATERIALS AND METHODS

To achieve the objective proposed, the data available from the National Agency of Water (ANA), obtained in the HIDROWEB database (ANA, 2014) were used. Data of the stations located in the Pantanal were entered in a Microsoft Excel spreadsheet, with the geographical coordinates and the values of the various parameters (DO, CO_2, pH, color, turbidity, etc.). The stations were entered into a Geographic Information System (ESRI, 2010), along with the main Pantanal rivers which were drawn using the orbital images. For processing the drainage patterns automatic tracing was done with the Digital Elevation Model (DEM) prepared with data from the Shuttle Radar Topographic Mission - SRTM 90m (USGS, 2006). Data in the literature were used for the evaluation of the proposal. Geocover Circa 1990 mosaic (MDA FEDERAL, 2004) were used to locate the areas experiencing the greatest flooding, thereby enabling the definition of the excerpts of the classified rivers. Data on water flows in the Pantanal were also utilized for this definition (Figures 1 and 2).

The evaluation of intensity of *dequada* was done by the duration of phenomenon, which was expressed in months, and by average DO on months when these values were less than 3 $mg.L^{-1}$. The stations that showed values higher than that value were considered to have not experienced this phenomenon.

To express the *dequada* intensity, two qualitative and quantitative methods were tested, which the first of them is expressed by equation $I = \frac{D}{DO*}$ [Eq. 1]; where I is the intensity of the phenomenon; D is the duration in months; and DO* is the average dissolved oxygen values less than 3 $mg.L^{-1}$. The DO values of the *dequada* phenomenon are grouped in Table 1, and the intensity value of the phenomenon is calculated by Equation 1. The intensity of the phenomenon is classified as weak, moderate and strong based on the intensity value calculated for each station, as shown in figure 3.

In the second method the DO as well as the duration of phenomenon were classified. The final classification was the sum of these two classifications. For the classification of DO and duration, weights were assigned according to their values, ranging from 1 to 3, which indicated weak, moderate or strong intensity. For values of $0<DO<1$ weight 3 has been assigned; for values of $1<DO<2$ weight 2; and for values of $2<DO<3$ weight 1. The same criterion was applied for the duration ranging from one to six months. Thus, a weight of 1 was given for durations of one to two months; a weight 2 for three to four months; and a weight of 3 for five to six months' duration. This method showed the expected results, which varied widely (OLIVEIRA et al, 2013; CALHEIROS; FERREIRA, 1996). Thus, we concluded that the first method was the more suitable one for the analysis proposed, and therefore, only the first method will be presented in this paper.

RESULTS AND DISCUSSION

The phenomenon of *dequada* was noted extending from Cáceres to Porto Murtinho in the Paraguay River, and the high intensity more common occurrence of this event was observed near the confluence of the Cuiabá River, close to Serra do Amolar. However, the phenomenon presents low-high intensity in the Cuiabá River.

In a study by EMBRAPA on the Pantanal (OLIVEIRA et al, 2013) the *dequada* phenomenon was found to be linked with changes in the physical and chemical characteristics of the water, depletion of the DO (<3 $mg.L^{-1}$) and an increase in the free CO_2 (> 100 $mg.L^{-1}$), which are the main factors responsible for water quality deterioration. Prior studies show that the average DO concentration in the Paraguay River, apart from the rainy season, is above 5.0 $mg.L^{-1}$; however, during the flooding months the value of this parameter drops to less than 3.0 $mg.L^{-1}$ (OLIVEIRA et al, 2013). In the same period, the values of dissolved CO_2 increase from 6.0 $mg.L^{-1}$ to above 100.0 $mg.L^{-1}$. The pH also reveals significant changes from 6.5 to 7.0 to 5.0. As demonstrated in the studies by Oliveira et al, (2013), and Calheiros and Ferreira (1996) the duration of the water remaining with low DO values (<3 $mg.L^{-1}$) is also a condition that favors the phenomenon of *dequada*. Thus, it is possible to ascertain the intensity of this phenomenon using these two parameters (DO and duration). The longer the duration the water remains with DO values less than 3 $mg.L^{-1}$, and the lower the DO values, the greater the intensity of the incidence of *dequada*. Therefore, we can deduce that the intensity of the phenomenon is directly proportional to the duration and inversely proportional to the DO.

Table 1 - Calculation of intensity of dequada taking into consideration the duration and the value of the dissolved oxygen (DO). Duration in months if the mean DO value is less than 3 mg.L^{-1}. Fig. 3 shows location of the stations

Station	Code	Name	DO *	Duration	Intensity
1	66070010	Jusante de Cáceres	3	1	0.33
2	66090000	Descalvados*	0	0	0
3	66120000	Porto Conceição	1.1	3	2.73
4	66751000	Montante Foz Rio São Lourenço	1.4	3	2.14
5	66801000	Pesqueiro Serra Negra (Amolar)	1.21	3	2.48
6	66810000	São Francisco*	1.92	1	0.52
7	66810500	Foz	2.07	3	1.45
8	66811000	Montante Captação d'água Corumbá	1.91	2	1.05
9	66821000	Jusante Marinha	1.79	3	1.68
10	66894000	Rio Taquari-Foz	1.62	6	3.70
11	66895000	Porto da Manga*	2.84	1	0.35
12	66921000	Rio Miranda-Foz	2.27	2	0.88
13	66971000	Jusante Forte Coimbra	0.28	1	3.57
14	66270000	Santo Antônio do Leverger	0	0	0
15	66296000	Jus. de Barão de Melgaço	0	0	0
16	66341000	Porto Cercado	2.89	1	0.35
17	66660000	Montante Foz Rio Itiquira	1.35	5	3.7
17	66665000	Jusante Foz Rio Itiquira	2.52	3	1.19
18	66750001	Retiro Fazenda Recreio	2.93	3	1.02
19	66449000	Mont. Conf. com Rio São Lourenço	0	0	0
20	66527000	Montante Foz Rio Piquiri	0	0	0
21	66481500	Montante Foz Rio Correntes	0	0	0
22	66945800	Foz Córrego Agogô	0	0	0
23	66886500	Jusante Foz Rio Taboco	1.9	1	0.53
24	66886800	Ponte Rodovia MS-170	1.7	1	0.59
25	66891000	Fazenda Tupaceretã	1.9	1	0.53
26	66911000	Ponte Rodovia BR-262 – Miranda/Bodoquena	0	0	0
27	66920500	Mont. Foz Rio Aquidauana	0	0	0

In station 17, the area where the Cuiabá River receives the waters of the São Lourenço River (Figure 3), reveals a long and high intensity *dequada* phenomenon. This region is characterized by long periods of flooding and high rates of sediment deposition by the São Lourenço River (ASSINE et al, 2014). Immediately beyond this point the water quality of the Cuiabá River improves considerably due to the entry of the Piquiri River with its high DO values (Figure 5). The waters from the Piquiri River would then be the cause for the improvement in the water quality of the Cuiabá River in the Retiro Fazenda Recreio station, downstream of the confluence of the Cuiabá River with Piquiri River. This is because the Piquiri River has a relatively small floodplain, limited to the area between the Taquari and São Lourenço megafans (PUPIM et al, 2014).

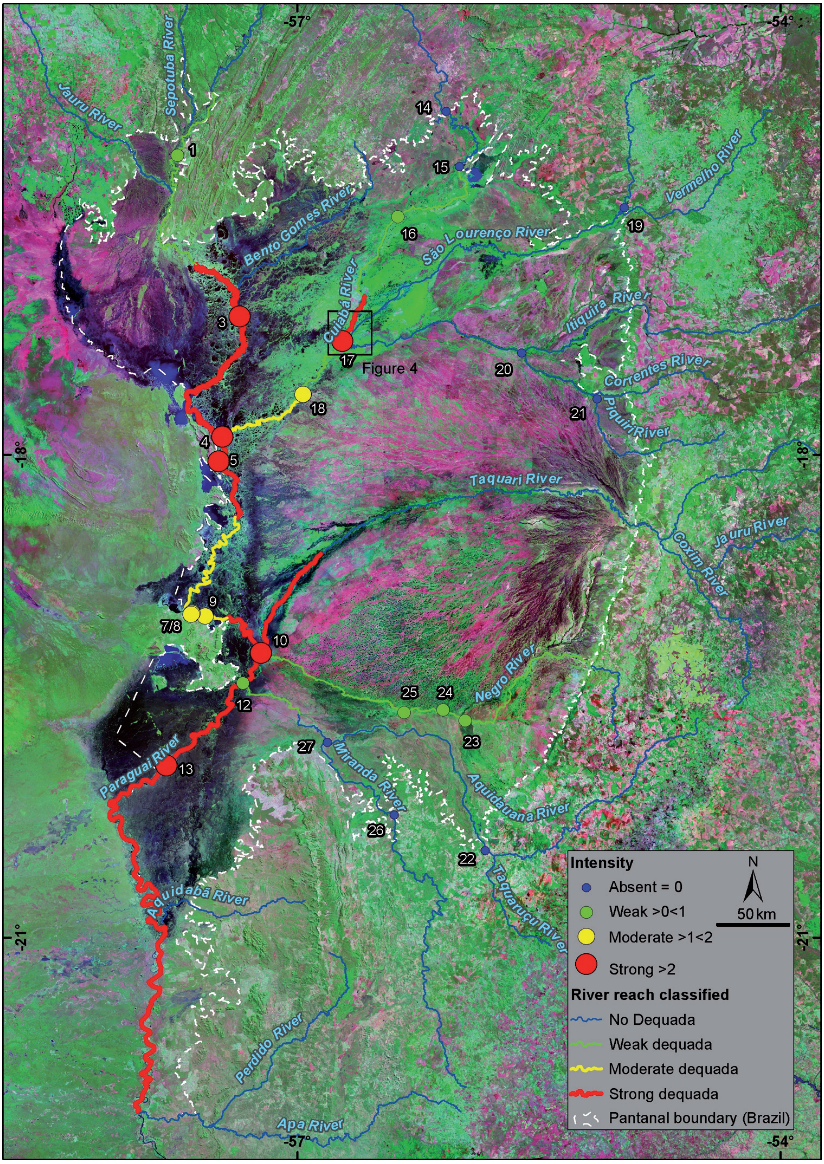

Figure 3 - Classification of the *dequada* intensity based on the concept of this study, in which the intensity of the *dequada* phenomenon is linked with the DO and duration according to Eq 1. GeoCover Circa 1990 mosaic (MDA Federal, 2004). The values of each station are listed in Table 1. The colored circles indicate the stations with the measuring DO and their colors signify the intensity of the *dequada*: blue = no *dequada*; green = weak; yellow = moderate; red = strong. The same applies to the colors of the rivers rating snippets. Coordinate system is cylindrical projection, SAD-69 datum

Prior to meeting the Paraguay River, the Cuiabá River returns to conditions more favorable to the *dequada* event, a fact that should be related to the low dynamism of the water on the plain and the resulting drop in the DO value of the water.

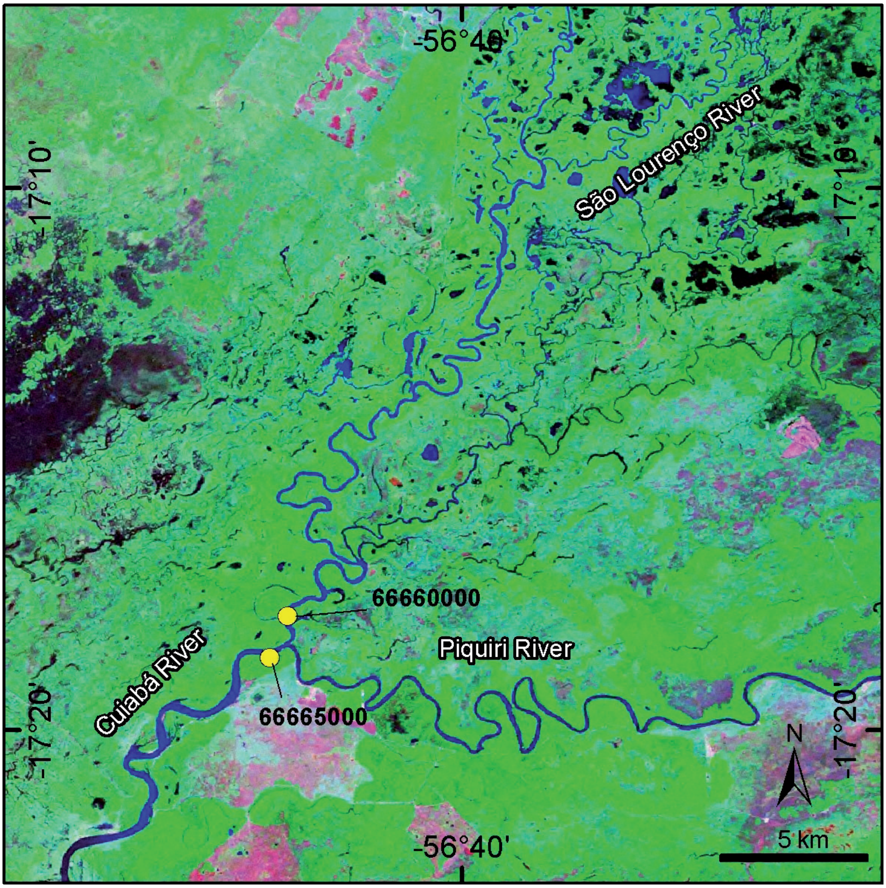

Figure 4 - Stations with water quality that reveals the increase in the dissolved oxygen (DO) in the Cuiabá River after receiving the waters of the Piquiri River. GeoCover Circa 1990 Mosaic (MDA FEDERAL, 2004). Cylindrical projection, SAD-69 datum

On analysis, the DO values in the Paraguay River reveal that the *dequada* phenomenon is connected with the flood pulse of the Pantanal. Here, values less than 3.0 $mg.L^{-1}$ are recorded from January to March in the northern region of the Pantanal, and in April-May in the southern part (Figure 6).

Over a ten-year period (2003-2012) this phenomenon was found to occur with greater intensity in the years of flood and strong intensity, preceded by the dry years. This is a proven fact as the year 2011 was a strong and full year, recording the lowest DO values at most of the recording sites; and this year was preceded by dry years.

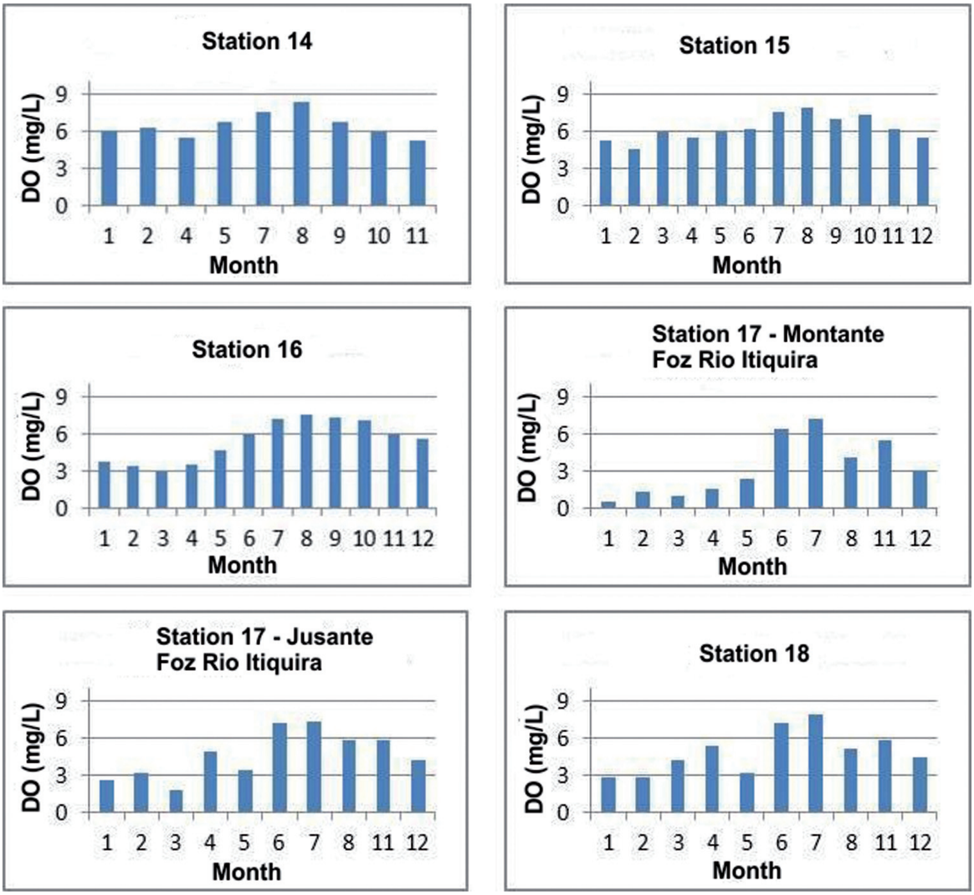

Figure 5 - Average values of dissolved oxygen (2003-2012) in the Cuiabá River

Stations found in areas near the plateau do not have any likelihood of the incidence of the *dequada* phenomenon, according to the works of Oliveira et al, (2013) and Calheiros and Ferreira (1996). *Dequada* was observed to occur preferentially in rivers possessing a wide floodplain; however, the stretches of rivers with confined plains have no probability of this phenomenon occurring (Correntes, Piquiri, Itiquira and São Lourenço rivers).

Another noteworthy factor is seen in the Jusante Marinha station (9), located in the city of Ladário-MS. This region showed a moderate intensity *dequada*, which appears unusual, as this region experiences a huge magnitude of floods. Therefore, the intensity calculated in this point is by the fact of in this region the Paraguay River loses its water to the upstream plain (in São Francisco station), and this water returns to the river just downstream of Ladário at the confluence with the Paraguay-Mirim River as demonstrated by Macedo (2013) (Figure 2D). As most of the water that overflows into the floodplain does not return to the Paraguay River, the phenomenon of *dequada* is softened in Jusante Marinha station.

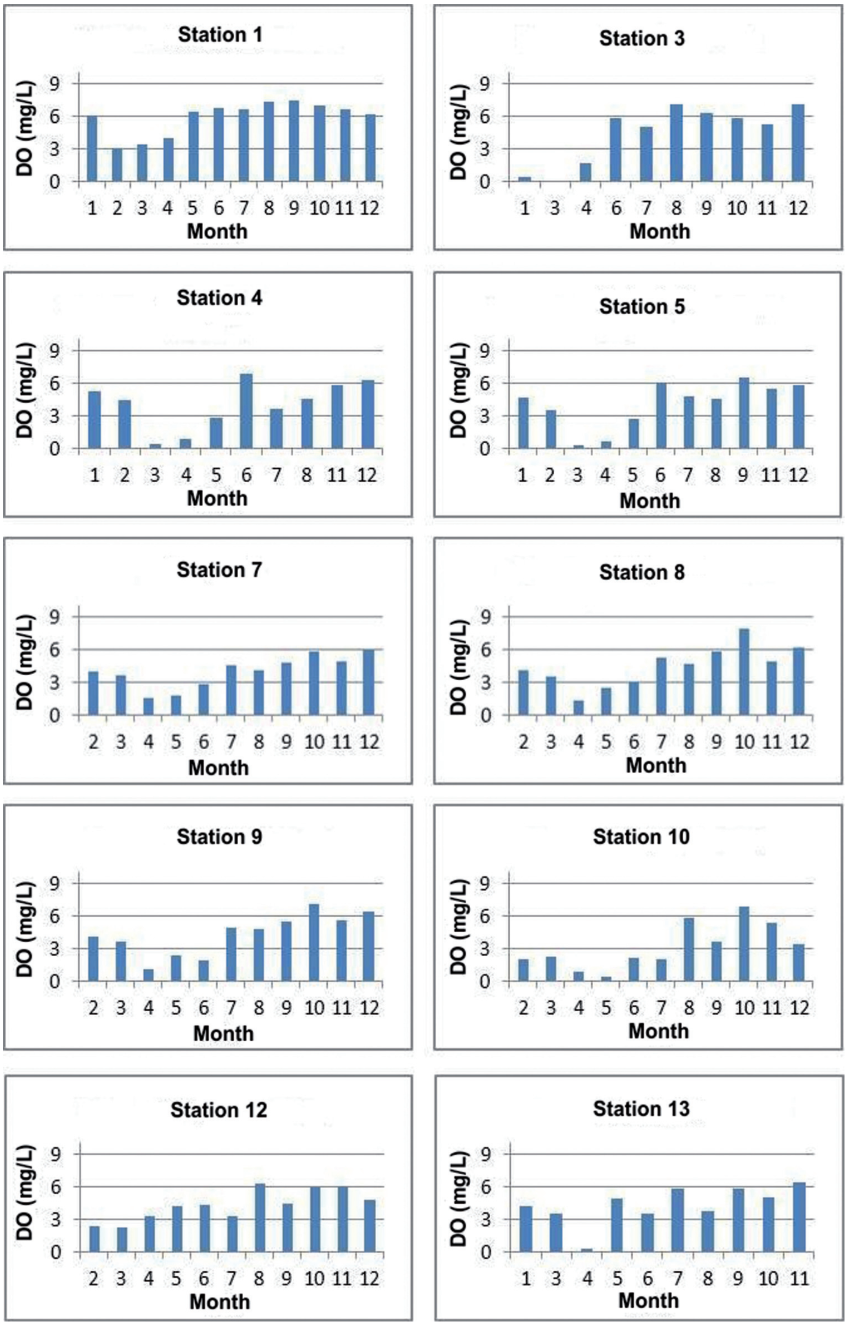

Figure 6 - Average values of dissolved oxygen (2003-2012) in the Paraguay River

Another interesting aspect are the results for the station at the mouth of the Miranda River (12). This region was rated as having a low intensity *dequada*, although, about 25 km upstream at the mouth of the Taquari River, an intense occurrence was observed. Classification of the station at the mouth of the Miranda River can be explained by the fact that the Paraguay River receives the waters of the Miranda River, which shows no deterioration in the water quality. Furthermore, it is important to note that the Paraguay River in this region receives the waters of the Negro River, which demonstrates low intensity of *dequada*.

CONCLUSIONS

The *dequada* phenomenon is induced by the natural deterioration of the physical and chemical quality of the water bodies of the Pantanal. The qualitative and quantitative method proposed, involving the basic parameter of dissolved oxygen levels (DO), enabled the determination of the regions where the intensity of *dequada* is weak, moderate or strong. The map proposed defines stretches of rivers that experience the highest probability of occurrence of this phenomenon based on the intensity. The Paraguay River is the water body more susceptible to *dequada*, based on the full intensity; and *dequada* intensity is found to be greater when the year of flood with more intense *dequada* was preceded by a drier year. This finding also emphasizes that this phenomenon has a hydrological basis, or is controlled by the quality and volume of the water provided by the Paraguay River tributaries. In this work we found that the water exchange between channel-floodplain is one of the main factors that interfere with the intensity of the phenomenon. This is because the water overflow must return to the channels so that the phenomenon is intensified. However, it is clear that the lack of data makes it difficult to proceed with further analysis of the phenomenon. Thus, the main deduction that can be drawn from this work is to request an increase and improvement in the quality of the water data and hydrological regime of the rivers and lakes in the Pantanal. This would facilitate a better and deeper analysis of the phenomenon.

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