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Inovações e Soluções Sustentáveis em Engenharia Ambiental

Water quality modeling in the Paraguay River basin using HEC-RAS

Modelagem da qualidade da água na região hidrográfica do Rio Paraguai utilizando o HEC-RAS

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ABSTRACT

The Upper Cuiabá River Basin, located in the Planning and Management Unit P4 (UPG-P4) on the plateau of the Paraguay River Basin, is an area of significant interest for water quality control. This region, which is home to approximately one million people, is experiencing rapid agricultural expansion. Being upstream of the Pantanal, one of the largest wetlands in the world, it becomes a region of great importance for environmental management. The primary water quality issues in the Paraguay River Basin are caused by the transport of sediments and diffuse pollutants from the plateau to the Pantanal. In this context, this study evaluated the impact of phosphorus control measures in UPG-P4 on the water quality of the Cuiabá River, using the HEC-RAS software for steady-state one-dimensional modelling. Four scenarios were simulated in the study, showing that the phosphorus limits of Class 2 of CONAMA Resolution 357/2005 were met only in Scenario 1 (an 80% reduction of phosphorus in pasture and agricultural areas), and only in the section between the Manso River and the beginning of the urban area of Cuiabá. The study found that pasture areas have a more significant impact than agricultural areas, and the model proved useful for planning water quality control and can be adapted for other regions of the Paraguay River Basin..

Keywords: Diffuse pollution; Mathematical modelling; Water quality; HEC-RAS

RESUMO

A Bacia do Alto Rio Cuiabá, localizada na Unidade de Planejamento e Gestão P4 (UPG-P4), no planalto da Bacia do Rio Paraguai, é uma área de grande interesse para o controle da qualidade da água. A região, que abriga cerca de um milhão de pessoas, também, está em franca expansão agropecuária e como fica à montante do Pantanal, que é uma das maiores áreas alagadas do mundo, passa a ser uma região de grande importância para o controle ambiental. Os principais problemas de qualidade da água na Bacia do Paraguai são causados pelo carreamento de sedimentos e poluentes difusos do planalto para o Pantanal. Neste contexto, este estudo avaliou o impacto de medidas de controle de fósforo na UPG-P4 sobre a qualidade da água do Rio Cuiabá, utilizando o software HEC-RAS para modelagem unidimensional estacionária. No estudo foram simulados quatro cenários, mostrando que os limites de fósforo da Classe 2 da Resolução CONAMA 357/2005 foram atingidos apenas no Cenário 1 (redução de 80% do fósforo em áreas de pastagem e agrícola), e somente no trecho entre o Rio Manso e o início da zona urbana de Cuiabá. O trabalho constatou que as áreas de pastagem têm impacto mais significativo que as agrícolas e o modelo mostrou-se útil para o planejamento do controle da qualidade da água e pode ser adaptado para outras regiões da Bacia do Paraguai.

Palavras-chave: Poluição difusa; Modelagem matemática; Qualidade da água; HEC-RAS

1 INTRODUCTION

Located on the plateau of Hydrographic Region (HR) of the Paraguay River, the Upper Cuiabá River Basin is crucial not only for its biodiversity and the presence of the Pantanal, one of the largest wetlands in the world, but also for facing challenges arising from agricultural expansion and population growth. Human activities typically end up intensifying water pollution through the runoff of pollutants, including phosphorus, a key indicator of the level of anthropization of areas and its impact on water quality (Abranches, 2017) (Ana, 2018) (Alho et al., 2019).

In this sense, a methodology was proposed using version 4.1.0 of the HEC-RAS software to analyze how phosphorus, from agricultural practices, affects the water quality of the Cuiabá River. The work carries out simulations of scenarios with different pollution mitigation strategies, focusing especially on the reduction of phosphorus, which can range from moderate interventions to measures that reduce its concentration by up to 80%.

The focus on measures to control phosphorus load is strategic, as this element is one of the main indicators of environmental degradation caused by human activities, directly affecting water quality and the health of aquatic ecosystems. Through this approach, the study aims not only to quantify the impacts of diffuse pollution, but also to guide the creation of public policies and practices for sustainable management of water resources, essential for the conservation of biodiversity and the maintenance of ecosystem services in the Pantanal and beyond.

2 MATERIALS AND METHODOLOGY

2.1 Study Area

The plateau region in the Paraguay HR forms a kind of surrounding barrier around the entire Pantanal, and maintains, through the springs and the plateau-plain water flow, the flood and ebb cycle of the Pantanal plain (Mercante et al., 2011), therefore, the Pantanal is a region very sensitive to the impacts caused on the plateaus (Franco *et al.*, 2013).

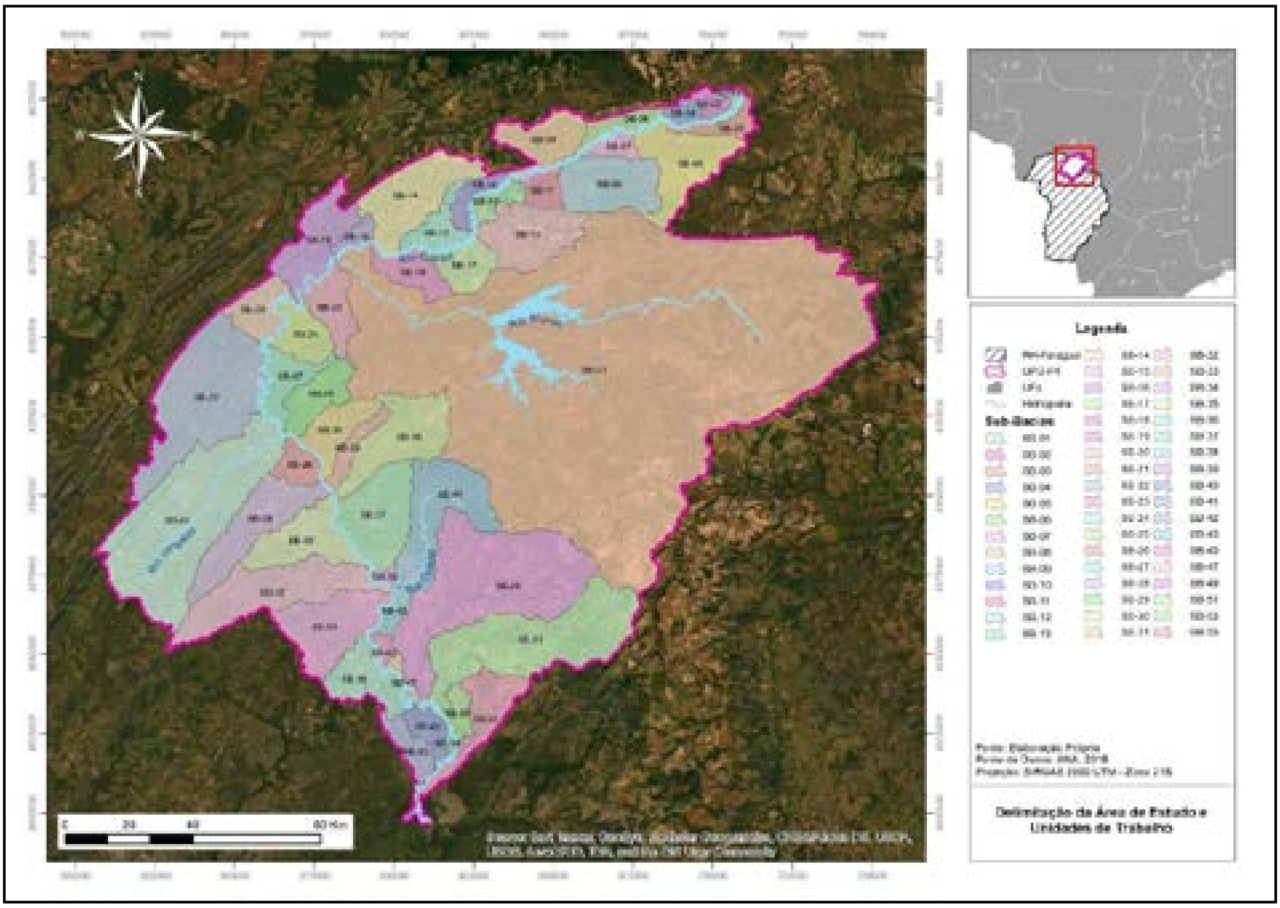
In this context, the Upper Cuiabá River Planning and Management Unit (UPG-P4) (Figure 1), covering a total area of 29,232 km² and located in the northern portion of the Paraguay HR, emerges as a critical point for the control of diffuse pollution. This UPG, located in the most populous and densely populated region of the Paraguay HR, with approximately one million inhabitants (IBGE, 2019), and with an accelerated expansion of the agricultural sector (WWF and SOS Pantanal, 2015), is located in the Pantanal plateau belt.

For effective strategic planning, it was decided to use the river sub-basin as the working unit, given that spatialization of information is crucial. The Brazilian Otto-Coded Hydrographic Base (OB), made available by the National Water and Sanitation Agency (ANA) in its geospatial metadata portal, was used. The OB is prepared based on the digital cartography of the Brazilian hydrographic network, organized in such a way as to provide hydrologically consistent information. It represents the hydrographic network in segments between the points of confluence of watercourses, called otto-basins, which are coded according to the Otto Pfafstetter system. This representation is topologically consistent, correctly reflecting the flow of rivers in their connected and directional configuration.

The sub-basins were identified using the Cuiabá River as a reference, looking from upstream to downstream. The sub-basins with discharge on the left bank of the river were named with the code SB-XX, where XX is an odd sequence. The sub-basins with discharge on the right bank were named SB-YY, where YY is an even sequence.

The delimitation analysis resulted in the identification of 48 sub-basins, with 27 located on the left bank and 21 on the right bank (Figure 1).

Figure 1 – Delimitation of the Study Area and Work Unit



Source: By the authors (2024)

2.2 Geospatial, Hydrological and Water Quality Data

Georeferenced data from fluviometric and water quality stations were also used, facilitating direct correlation with the hydrological and water quality data collection sites. For hydrological data, this study relied on flow time series collected at the basin's fluviometric stations. The data were obtained through the HidroWeb v3.1.1 portal (snirh.gov.br/hidroweb).

Six fluviometric stations were used to characterize the river regime of the Cuiabá River, with monthly flow averages calculated for each one: Marzagão - 66140000, Quebó - 66160000, Rosário Oeste - 66250001, Acorizal - 66255000, Cuiabá - 66260001, Barão De Melgaço - 66280000.

Regarding water quality, 13 stations were considered to characterize the study area: 6133000 – Rosário Oeste, 66140000 – Marzagão, 66245001 – Nobres, 66250002 – Bridge in Rosário Oeste MT 010, 66255000 – Acorizal, 66259200 – Passagem da Conceição / Cuiabá, 66259301 – Downstream of Córrego Mané Pinto, 66259305 – Downstream of Córrego Barbado, 66259309 – Downstream of Córrego São Gonçalo, 66260151 – Jusante of Córrego Ribeirão dos Cocais, 66270000 – Santo Antônio do Leverger, 66280000 – Barão de Melgaço, 66296000 – Downstream of Barão de Melgaço. The parameters observed included Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD) and Total Phosphorus (TP), essential for assessing the degree of water pollution and the conditions for aquatic life.

In this work, the HEC-RAS software version 4.1.0, developed by the U.S. Army Corps of Engineers, was used to simulate the hydrodynamic behavior of the Cuiabá River and the distribution of pollutants under different conditions of pollution load management, as this software is capable of performing detailed analyses of one-dimensional flow, sediment transport, and water quality in river systems.

2.3 Regionalization of Flow Rates

Para a simulação de qualidade da água, foi necessário simular as condições hidráulicas do rio. Para tal, foi necessário que cada uma das sub-bacias da área de trabalho alimente o modelo de qualidade da água com dados de vazão e de qualidade (este último determinado pela concentração, em mg/L, dos parâmetros de interesse). A combinação destes dados resulta nas cargas de aporte lateral no modelo. Neste sentido, como não há medições de vazão em todas as sub-bacias de trabalho, foi utilizado o conceito de regionalização por vazão específica, calculada a partir da Equação 1.

For the water quality simulation, it was necessary to simulate the hydraulic conditions of the river. To this end, it was necessary for each of the sub-basins in the work area to feed the water quality model with flow and quality data (the latter determined by the concentration, in mg/L, of the parameters of interest). The combination of these data results in the lateral input loads in the model. In this sense, since there are no flow measurements in all the sub-basins under study, the concept of regionalization by specific flow rate was used, calculated from Equation 1.

$$Q_{esp1} = \frac{Q_i}{A_i} \quad (1)$$

Where:
Qesp1: specific flow rate for the fluviometric station (average, flood or dry season), in $m^3/s{\cdot}.km^2$
Qi: flow rate measured at fluviometric station i (average, flood or dry season), in m^3/s
Ai: area of influence of the station at point i, in km^2

The areas of each sub-basin were then determined and the specific flows were calculated based on data from three fluviometric stations in the work area (stations 66160000, 66255000 and 66280000). The choice of three different stations to calculate the specific flow took into account the area of the Upper Cuiabá River basin (UPG-P4), which, because it has more than 29,000 km², could distort the specific results for each sub-basin. Thus, a combination of the three fluviometric stations was made to determine more realistic specific flows for each area of influence of the fluviometric stations.

Having the specific flows calculated, the contribution flows of each sub-basin were determined, multiplying the area of the sub-basin by its corresponding specific flow, according to the area of influence of each fluviometric station (Equation 2).

$$Q_{SB} = Q_{ESPI} . A_{SB} \quad (2)$$

Where:
QSB: total flow of the sub-basin (average, flood or drought), in m^3/s
Qespi: specific flow 1 or 2, according to the station of influence of the sub-basin, in $m^3/s{\cdot}.km^2$
ASB: area of the sub-basin, in km^2.

2.3 Characterization and quantification of pollution sources in UPG-P4

Considering that the objective of this work was to characterize the impact of diffuse pollution, it was necessary to characterize and quantify other sources of pollution in the basin in order to obtain a realistic distribution of pollutant loads and, thus, obtain more accurate water quality results. Three different pollution sources were characterized and quantified: Diffuse Pollution (generated by surface runoff); Treated Domestic Sewage and Untreated Domestic Sewage, which were characterized in Treated and Untreated Sewage Flow Rates.

To quantify the pollutant loads from domestic sewage, the following were identified: the municipalities belonging to UPG-P4 and their municipal headquarters; the total and urban population of each municipality; and the percentage of urban population served by sewage.

The delimitation of the municipalities belonging to UPG-P4 and their municipal headquarters were identified through IBGE cartographic bases (IBGE, 2015), and the domestic sewage loads generated by the rural population were not considered in this study.

The total and urban populations of each municipality, as well as the coverage of sewage services were obtained from different sources, such as: Sistema Nacional de Informações Sobre Saneamento Ambiental – SNIS (SNIS, 2019); Atlas Esgotos: Despoluição de Bacias Hidrográficas (ANA, 2017b); Plano de Recurso Hídricos da Região Hidrográfica do Rio Paraguai (ANA, 2018) e Planos Municipais de Saneamento Básico, in such a way that the flow rates of treated and untreated sewage for each municipality were calculated based on the equations presented in Table 1.

Table 1 – Equations used to calculate treated and untreated sewage flow rates

Parameter	Equation	Number of the Equation
Total Untreated Sewage Flow	$Q_{ENT}=Q_{ENTG}+Q_{Inf}$	(3)
Generated Untreated Sewage Flow	$Q_{ENT\_G}=\frac{P_i.q_i.T_R}{86400}$	(4)
Infiltration Flow	$Q_{Inf}=T_i.Q_{ENT\_G}$	(5)
Treated Sewage Flow	$Q_{ET}=\frac{P_a.q_i.T_R}{86400}$	(6)

Where:
Q_{ENT}: untreated sewage flow rate per municipality (L/s
Q_{ENTG}: untreated sewage flow rate generated per municipality (L/s)
Q_{Inf}: infiltration flow rate (L/s)
P_i: Population without sewage service, in inhabitants
T_R: Return rate, equal to 0.8
T_i: Infiltration rate, equal to 0.2
Q_{ET}: treated sewage flow rate per municipality (L/s)
P_a: Population with sewage service, in inhabitants
q_i: Per capita water consumption, equal to 150 L/inhab.day
Source: By the authors (2024)

Based on the location of the municipal headquarters, the sub-basins in which the contributions of pollutant loads from domestic sewage would occur were identified. Thus, the sewage flows of municipalities located in the same sub-basin were added together, as indicated in Equations 7 and 8.

$$Q_{ENT_{SB}} = \sum_i Q_{ENT_i} \quad (7)$$

Where:
$Q_{ENT_{SB}}$: total untreated sewage flow rate of the sub-basin, in m³/s
Q_{ENT_i}: untreated sewage flow rate of municipality i, in m³/s

$$Q_{ET_{SB}} = \sum_i Q_{ET_i} \quad (8)$$

Where:
$Q_{ET_{SB}}$: total treated sewage flow rate of the sub-basin, in m³/s
Q_{ET_i}: treated sewage flow rate of municipality i, in m³/s

The physicochemical characteristics of untreated domestic sewage were determined according to Von Sperling (2007), who determined typical ranges and values of the characteristics of raw domestic sewage in developing countries. For this study, the chemical parameters required for water quality simulations in the mathematical model used are the following: Dissolved Oxygen (DO); Biochemical Oxygen Demand (BOD); Organic Nitrogen (NOrg); Ammoniacal Nitrogen (NAmon); Nitrate (NO_3); Nitrite (NO_2); Organic Phosphorus (POrg); Orthophosphate (PO_4).

Even if the parameters of main interest of the study do not include all of these, it is necessary to quantify them for the correct functioning of the water quality simulation in the mathematical model.

In untreated domestic sewage, nitrogen appears predominantly as organic nitrogen and ammoniacal nitrogen, however, the forms of nitrate and nitrite also make up its fractions, thus, the total nitrogen concentrations are determined in the following:

Total Nitrogen (TN) = Total Kjeldahl Nitrogen (TKN) + Nitrite (NO_2) + Nitrate (NO_3)

Where TKN = NAmon + NOrg

As for Phosphorus, it manifests itself in untreated domestic sewage predominantly as organic phosphorus and orthophosphate, therefore, total phosphorus concentrations are determined as:

Total Phosphorus (TP) = Organic Phosphorus (POrg) + Orthophosphate (PO_4)

In the mathematical model adopted, no load reduction was considered between sewage disposal and entry into the main receiving body, thus the same quality of raw sewage was considered for all municipalities.

Table 2 – Quality of raw sewage considered in this study. Source: Von Sperling (2007)

Quality Parameter	Concentration in Untreated Sewage (mg/L)
OD	0
DBO	347.2
NOrg	27.8
NAmon	41.7
NO_3	2.1
NO_2	0.3
TN	69.4
POrg	2.1
PO_4	4.9
TP	6.9

Source: By the authors (2024)

For the quality of treated sewage, conservative premises for effluent disposal were considered, following the guidelines of CONAMA Resolution No. 430/2011. This premise is considered conservative since the resolution establishes the minimum conditions and standards for the discharge of effluents from Sanitary Sewage Treatment Systems. The discharge quality standards recommended in this resolution and which were considered in this study are 138.9 (mg/L) for BOD and 20.0 (mg/L) for NAmon. For the other elements indicated in Table 2, which do not have established standards, the discharge concentrations were the same as those of raw sewage, with the exception of DO, which was considered at a concentration of 1.0 (mg/L).

To quantify the loads of diffuse origin, the surface runoff flows of each sub-basin were initially determined. These flows were determined from Equation 9.

$$Q_{ES}=Q_{SB}-Q_{VB}-Q_{ENTSB}-Q_{ET\ SB} \quad (9)$$

Where:
Q_{ES}: surface runoff flow, in m³/s
Q_{SB}: total flow of the sub-basin, in m³/s: base flow, in m³/s: untreated sewage flow of the sub-basin, in (m³/s)
$Q_{ET\ SB}$: treated sewage flow of the sub-basin, in (m³/s)

Base flow corresponds to the subsurface flow that ensures the flow of the river even in times of drought. Thus, base flow was calculated considering Equation 10.

$$Q_{VB} = \frac{\sum Q_{SB_{estiagem}}}{\sum Q_{SB_{média}}} . Q_{SB} \quad (10)$$

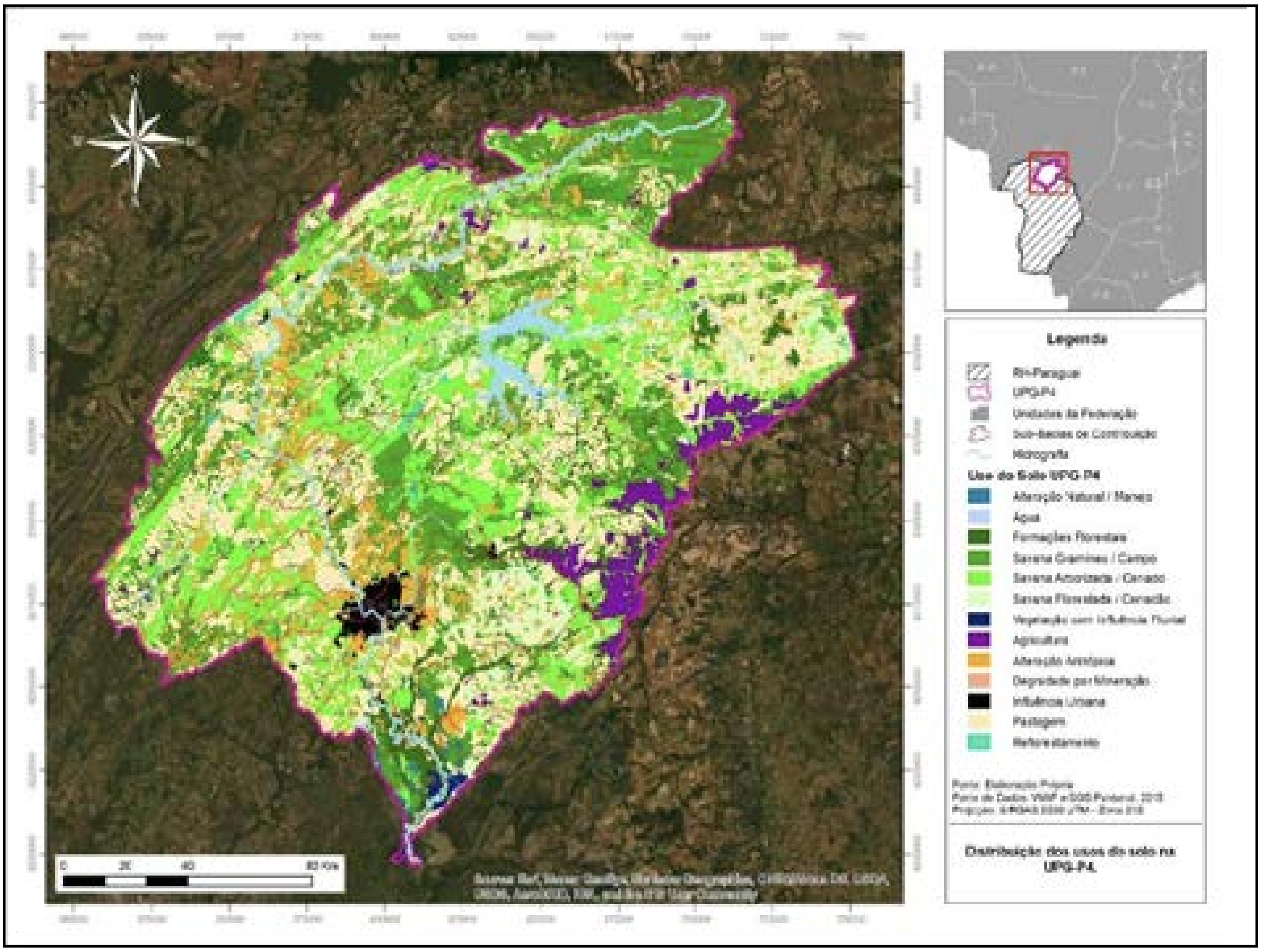
Where:
$\sum Q_{SB\ estiagem}$: accumulated flow of upstream sub-basins during the dry season, in m³/s
$\sum Q_{SB\ média}$:cumulative flow of the upstream sub-basins in the general average, in m³/s.

With the base flow of each sub-basin determined, the surface runoff flow of each sub-basin was calculated using Equation 9. To quantify diffuse loads, the concept of the Average Event Concentration (AEC), developed by the United States Environmental Protection Agency (USEPA), was used to serve as a measure of characterization of pollutants originating from each land use and which end up in water bodies during rainy events (Martins, 2017).

The AEC can be understood as the average concentration of DO, BOD, TN, TP or other parameter of interest associated with the surface runoff of a given area. To use this concept, it is necessary to determine the land uses of the basin, since surface runoff has different qualities depending on the land use category over which it flows. Thus, each land use is assigned specific AECs for each parameter of interest, making territorial occupation a fundamental component for the analysis of diffuse load.

The division of land use and occupation categories was based on the survey carried out by the partnership between WWF Brazil and the Instituto SOS Pantanal, with support from EMBRAPA Pantanal, which quantified the natural and anthropic areas in 2014, maintaining the history of monitoring land use in the Upper Paraguay Basin carried out since 2002 (WWF and SOS Pantanal, 2015). The survey classified, in the UPG-P4 area, 13 different land use categories, seven of which were classified as areas of Natural Use (Natural Change/Management; Water; Forest Formations; Grassy Savannah/Field; Wooded Savannah/Cerrado; Forested Savannah/Cerrado and Vegetation with Forest Influence) and another six as areas of Use with Anthropic Change (Agriculture; Anthropic Change; Degradation by Mining; Urban Influence; Pasture and Reforestation) according to Table 3 and Figure 2.

Figure 2 – Distribution of land uses in UPG-P



Source: by the authors (2024)

Table 3 presents the AECs and surface runoff coefficients used to determine the quality of surface runoff.

Table 3 – AECs and Surface Runoff Coefficients for each land use in UPG-P4

Land Use	Surface Runoff Coefficient	AEC (mg/L)			
		DO	BOD	TN	TP
Natural Change/ Management	0.30	4.00	0.50	0.00	0.00
Water	1.00	0.00	0.00	0.00	0.00
Forest Formations	0.20	4.00	0.50	0.00	0.21
Grassy Savannah/ Grassland	0.30	4.00	0.50	0.00	0.21
Wooded Savannah/ Cerrado	0.30	4.00	0.50	0.00	0.21
Forest Savannah/Cerrado	0.30	4.00	0.50	0.00	0.21
River-Influenced Vegetation	0.90	4.00	0.50	0.00	0.21
Agriculture	0.40	2.00	3.00	2.00	0.91
Anthropogenic Change	0.45	2.00	3.00	2.00	0.28
Mining Degraded	0.50	2.00	3.00	2.00	0.28
Urban Influence	0.80	1.00	8.00	3.00	4.90
Pasture	0.40	1.00	8.00	1.30	0.30
Reforestation	0.35	4.00	1.00	0.00	0.21

Source: Adapted from (Ana, 2018)

Then, the average concentrations of each component in each sub-basin were calculated based on the AEC of the identified land uses. Since each sub-basin has a variety of land uses, an average AEC per sub-basin was calculated considering a weighted average between the AECs of each land use, the area of each land use within the sub-basin and the Surface Runoff Coefficient associated with each land use (Equation 11).

$$\overline{CME_{sub-basin}} = \frac{\sum(A\times Rc\times CME)_i}{\sum(A\times Rc)_i} \tag{11}$$

Where:
A: area of land use i within the sub-basin, in km²
Rc: runoff coefficient associated with land use i, dimensionless
CME: average event concentration (AEC) for land use i, in mg/L.

Then, the average concentrations of each component in each sub-basin were calculated based on the AEC of the identified land uses. Since each sub-basin has a variety of land uses, an average AEC per sub-basin was calculated considering a weighted average between the AECs of each land use, the area of each land use within the sub-basin and the Surface Runoff Coefficient associated with each land use (Equation 11).

Considering that, as for domestic sewage, the chemical parameters required for water quality simulations in the mathematical model used are dissolved oxygen (DO), biochemical oxygen demand (BOD), organic nitrogen (NOrg), ammoniacal nitrogen (NAmon), nitrate (NO_3), nitrite (NO_2), organic phosphorus (POrg) and orthophosphate (PO_4), the partitions of each component of total nitrogen (TN) and total phosphorus (TP) were defined based on measurements taken by water quality monitoring stations, as shown in Table 4. Thus, the AECs of TN and TP were multiplied by the calculated partitions.

Table 4 – Nitrogen and phosphorus partitions considered for diffuse pollution in the water quality simulations of the Cuiabá River

Sub-Basin	Associated Quality Station	Partition (%)					
		NOrg	NAmon	NO_2	NO_3	POrg	PO_4
SB-01, SB-02, SB-03, SB-04, SB-05, SB-06, SB-07, SB-09, SB-08, SB-11, SB-13, SB-10, SB-15, SB-17	66133000	83.5%	4.5%	3.3%	8.7%	56.6%	43.4%
SB-12, SB-19, SB-14, SB-16, SB-21, SB-18, SB-23	66245001	72.9%	9.7%	4.6%	12.8%	68.3%	31.7%
SB-25, SB-20, SB-27, SB-22, SB-24, SB-29	66250002	67.4%	8.5%	6.1%	18.1%	73.0%	27.0%
SB-26, SB-31, SB-28, SB-33, SB-35, SB-30, SB-37, SB-32	66259200	75.2%	7.2%	3.7%	13.9%	69.6%	30.4%
SB-39	66259301	74.9%	7.8%	4.6%	12.6%	61.0%	39.0%
SB-41	66259305	64.6%	21.8%	3.7%	9.9%	56.1%	43.9%
SB-43, SB-34	66260151	77.4%	7.7%	3.0%	12.0%	60.0%	40.0%
SB-45, SB-47, SB-36, SB-49, SB-51, SB-53, SB-38, SB-55, SB-40, SB-42	66270000	72.8%	9.3%	4.5%	13.4%	9.6%	90.4%

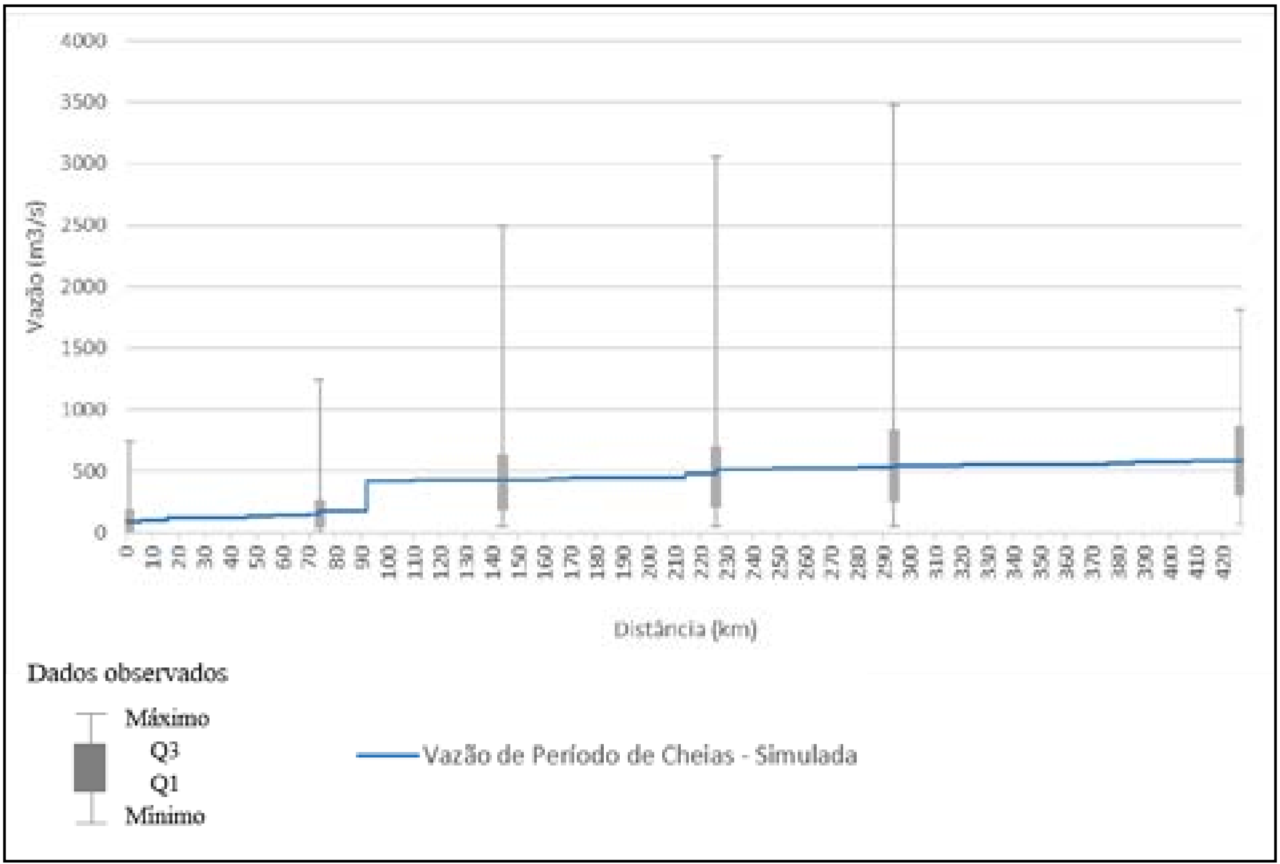
Source: By the authors (2024)

3 RESULTS AND DISCUSSION

For the hydraulic simulations, the steady-state flow module was used, representing constant hydraulic conditions (flow rates). The average flood flow condition was used. The water quality conditions were simulated with data for all nine constituents required by the model's quality module (DO, BOD, NOrg, NAmon, NO_3, NO_2, POrg and PO_4).

The configuration of the model geometry involved defining the boundary conditions and lateral input points. The upstream boundary condition was established at the points where monitoring stations 66140000 and 66133000 are located, considering all upstream sub-basins as the first input to the model. All other sub-basins in the study area downstream of these points were treated individually as lateral inputs. A specific flow value was associated with each input point, totaling 40 input points in the model. After the flow simulation, the model results ended up in the curve shown in Figure 3.

Figure 3 –Model results (flow rates)



Source: by the authors (2024) Dados observados: observed data
Vazão do período de cheias: Flow rate of the flood period

Table 5 – Water quality scenarios for simulations in the Cuiabá River

Scenario	**Flow Rate Used**	**Diffuse Pollution Control**	**Controlled Parameter**		**About Which Land Use**
Base	Average of the Flood Period	NO	-	-	-
Scenario 1	Average of the Flood Period	YES	Total Phosphorus	80%	Agricultural and Pasture
Scenario 2	Average of the Flood Period	YES	Total Phosphorus	80%	Pasture Only
Scenario 3	Average of the Flood Period	YES	Total Phosphorus	80%	Agricultural Only

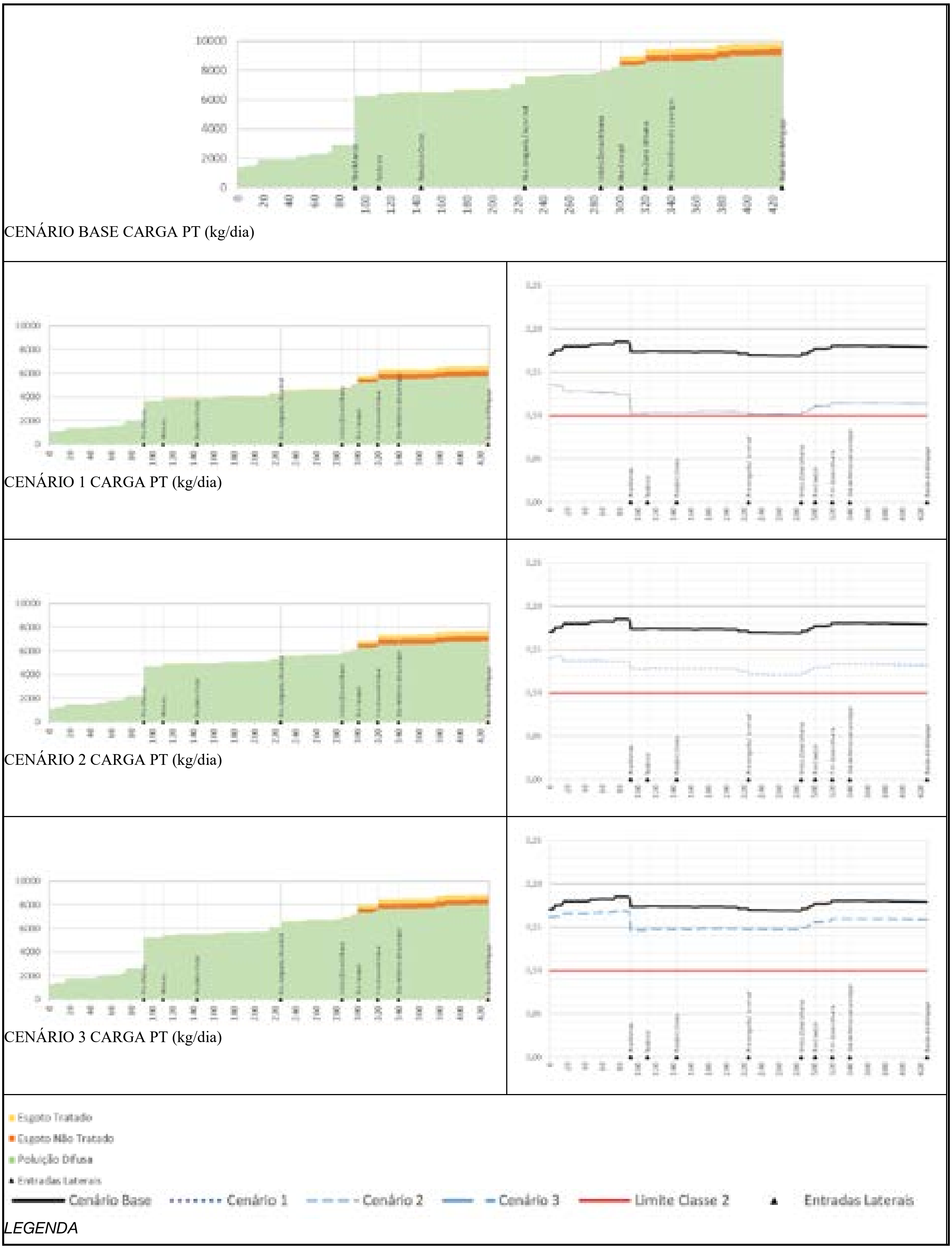
Source: By the authors (2024)

A jump in flows can be seen near the distance of 91 km. This jump corresponds to the entry of the Manso River sub-basin (SB-21), the largest sub-basin in the work area and which, therefore, contributes the largest flow input to the model. The box plots inserted in the graph correspond to the average flows observed along the river

It is possible to see that the simulated values present a satisfactory adherence to the observed values, being between the 1st (Q1) and 3rd (Q3) quartiles of the observed data of all stations, being considered sufficient for water quality simulations.

Total phosphorus concentrations in the Cuiabá River during the flood period do not meet the limit established by CONAMA Resolution No. 357/2005. Therefore, to reflect the application of diffuse pollution control measures in pasture and agricultural areas, a reduction coefficient of 80% was applied to the Total Phosphorus AEC for Livestock and Agricultural uses. This reduction rate was defined based on the successful implementation of large constructed wetlands, called Stormwater Treatment Areas (STAs) (Zhao and Piccone, 2020).

Figure 4 – Results of Total Phosphorus (TP) simulations in the Cuiabá River.



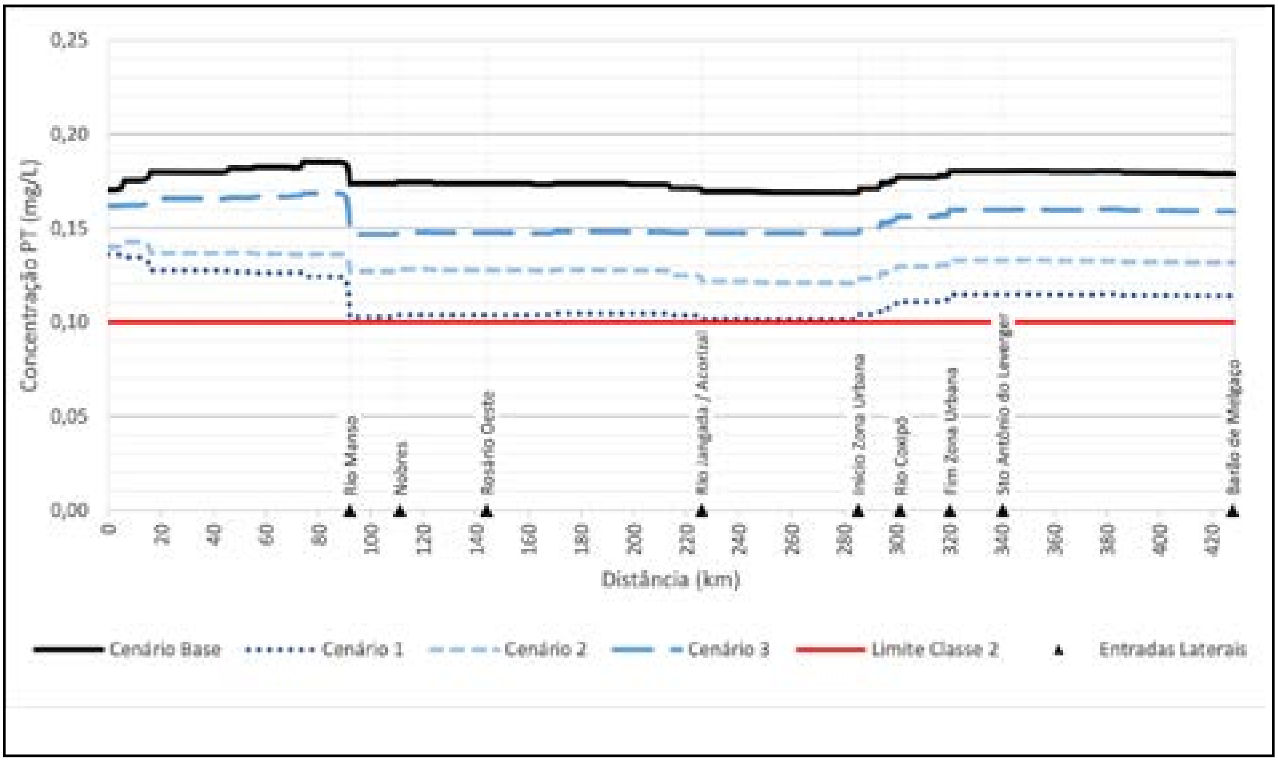
Source: by the authors (2024)

Figure 4 shows the accumulated phosphorus loads along the modeled stretch, both for the Base Scenario and for each of the other three simulated scenarios. The accumulated load graphs indicate the daily mass of total phosphorus that the modeled stretch accumulates along the river with the inflow of each sub-basin. It can be seen that, in the Base Scenario, this value reaches almost 10,000 kg TP/day, with the largest contribution coming from the Manso River sub-basin, which is directly related to its drainage area. The contributions of domestic sewage are noted only downstream of the beginning of the urban area of Cuiabá and Várzea Grande, since this is where almost all (close to 100%) of the population of the Upper Cuiabá basin resides. In general, the contributions related to Diffuse Pollution are the majority throughout the basin and in all scenarios. Up to the beginning of the urban area of Cuiabá and Várzea Grande, it represents 99% of the accumulation of phosphorus loads in all scenarios. Downstream from this point, it begins to have a slightly smaller representation, but still dominant, since it is in the order of 94% in the Base Scenario, 90% in Scenario 1, 92% in Scenario 2 and 93% in Scenario 3. With the loads coming from untreated sewage varying between 3% and 7% and from treated sewage between 4% and 6% of the total.

Figure 4 also presents the results of the water quality simulations in each scenario. In the Base Scenario, total phosphorus (TP) concentrations start at around 0.170 mg/L, which is already 70% above the limit established by law. With the lateral inputs of loads from the sub-basins along the river, this concentration reaches levels of up to 0.185 mg/L between distances 74 and 90 km of the modeled stretch. Near 90 km, there is a notable drop in phosphorus concentration. At this point, the Manso River (sub-basin 21) enters the river. Since this is the largest sub-basin in the work area, its discharge dilutes the phosphorus concentrations present in the Cuiabá River, improving water quality.

With this drop, phosphorus levels reach 0.174 mg/L. From there, the river receives contributions from the cities of Nobres, Rosário Oeste, Acorizal and the sub-basin of the Jangada River. Between the entrance of the Jangada River, at km 225, and the beginning of the urban area of Cuiabá and Várzea Grande, phosphorus concentrations in the river reach their lowest values, close to 0.169 mg/L. With contributions from the urban area between distances 285 and 320 km, phosphorus levels increase again, reaching approximately 0.180 mg/L. After this, lateral contributions are minimal and the values at the end of the simulated stretch are 0.179 mg/L. Thus, it can be seen that, even with the distance of more than 400 km traveled, due to the varied lateral contributions, phosphorus concentrations are on average 76% above the limit permitted by law throughout the modeled stretch.

Figure 5 – Results of Total Phosphorus (TP) simulations in the Cuiabá River – All Scenarios



Source: by the authors (2024)

Comparing the 4 scenarios with each other, presented together in Figure 5, it is possible to observe that Scenario 1 is the most optimistic and the only one with total phosphorus (TP) concentrations that are within the limit established by legislation in certain stretches of the modeled river, while Scenarios 2 and 3 are in an intermediate condition between the Base Scenario and Scenario 1, far from meeting Class 2.

Comparing Scenarios 2 and 3, the average phosphorus concentrations along the river modeled in Scenario 2 are lower than in Scenario 3. This is directly linked to the area occupied by each type of land use in the sub-basins. In the Upper Cuiabá River basin (UPG-P4), the area occupied by pasture is around 8,557 km^2, while the area for agricultural use is much smaller, around 1,066 km^2 (WWF and SOS Pantanal, 2015). Therefore, the reductions in phosphorus from surface runoff from pasture areas (Scenario 2) result in a greater impact on the quality of the Cuiabá River than reductions in agricultural areas alone (Scenario 3). The application of control measures in both uses (Scenario 1) results, as mentioned, in better water quality conditions.

In all scenarios, it is possible to observe the impact of the Manso River sub-basin on the waters of the Cuiabá River, always contributing to the reduction of phosphorus levels due to its high contribution flow.

4 FINAL CONSIDERATIONS

The simulations of the scenarios, using the mathematical model of water quality using the HEC-RAS software, configured and calibrated for the UPG-P4 area, showed that, although the application of diffuse pollution control measures has positive effects in all scenarios, the application in the simulated format would not be sufficient to meet the water quality limits along the entire simulated stretch. Scenario 1 was the only one that presented phosphorus concentrations at the limit required for Class 2, even so, this occurred only in a few kilometers of the studied stretch, which was between distances of 90 km and 285 km.

Even if all the measures to reduce diffuse loads proposed for pasture and agricultural areas were implemented, it would not be possible to achieve, on average, the phosphorus concentration limits required by law during flood periods. Even so, it was possible to observe that pasture areas, in comparison with agricultural areas, have a greater influence on the water quality of the Cuiabá River. This was observed by comparing the results of Scenarios 2 and 3 and is justifiable because the use of land for pasture is greater than for agricultural use in UPG-P4, representing approximately 29.3% (8,556.8 km²) of the river basin, while agricultural areas represent 3.6% (1,066.3 km²).

Based on the results obtained, it is necessary to seek alternatives to meet Class 2 requirements, either by considering the control of diffuse loads from areas other than pasture and agricultural ones or by defining alternatives that increase the proposed phosphorus removal efficiency. Even so, it is also necessary to conduct a critical assessment of the real impacts and improvements that meeting the maximum concentrations required by CONAMA Resolution No. 357/2005 would bring to the dynamics of the Pantanal. To this end, complementary studies would be necessary to assist decision-making within the Paraguay River Hydrographic Region.

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