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IRRIGATION AS A STRATEGY FOR ADAPTING TO CLIMATE CHANGE AND INTENSIFYING AGRICULTURE IN MATO GROSSO

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Dissertation submitted to the Applied Meteorology Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Magister Scientiae*.

Adviser: Marcos Heil Costa

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To my family.

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ABSTRACT

VITORINO, Flávia Barros, M.Sc., Universidade Federal de Viçosa, September, 2024. **Irrigation as a strategy for adapting to climate change and intensifying agriculture in Mato Grosso**. Adviser: Marcos Heil Costa.

Mato Grosso is a major contributor to Brazil's agriculture, leading in soybean, maize, and cotton production. In 2023/2024, the state's 12.7 million hectares of soybeans yielded 39 million tons, while maize and cotton, planted as secondary crops on 7 million and 1.5 million hectares, respectively, also produced strong yields. Approximately only 135,000 hectares are currently irrigated using center pivot, with most agriculture relying on rainfed systems and double cropping, which depends on a rainy season lasting at least 200 days. However, climate change threatens this model, with projected temperature increases, higher vapor pressure deficits, and altered precipitation patterns leading to shorter rainy seasons and increased water stress, potentially lowering yields—estimated to drop by 30 kg/ha per day of reduced rainy season duration. Given these challenges, this study explores irrigation as a climate adaptation strategy, integrating regional evapotranspiration, irrigation water uptake, discharge regionalization, and land suitability analyses. Findings indicate that agricultural intensification through irrigation is possible without additional deforestation, with over 6 million hectares for expansion under a shared water management system and nearly 2 million hectares under the current individual water granting system. However, limitations in Mato Grosso's monitoring network underscore the need for enhanced water data and robust management to support long-term irrigation expansion sustainably.

Keywords: irrigation; climate change; double cropping; water stress; intensification

RESUMO

VITORINO, Flávia Barros, M.Sc., Universidade Federal de Viçosa, setembro de 2024. **Irrigação como estratégia de adaptação às mudanças climáticas e intensificação da agricultura no Mato Grosso**. Orientador: Marcos Heil Costa.

Mato Grosso é um importante produtor agrícola do Brasil, liderando a produção de soja, milho e algodão. Na safra 2023/2024, os 12,7 milhões de hectares de soja do estado produziram 39 milhões de toneladas, enquanto o milho e o algodão, plantados como culturas de segunda safra em 7 milhões e 1,5 milhão de hectares, respectivamente, também apresentaram altos rendimentos. Atualmente, aproximadamente apenas 135.000 hectares são irrigados por pivô central, com grande parte da agricultura dependendo de sistemas de sequeiro e do plantio em segunda safra, que exige uma estação chuvosa de pelo menos 200 dias. No entanto, as mudanças climáticas ameaçam esse modelo, com projeções de aumento de temperatura, maior déficit de pressão de vapor e mudança nos padrões de precipitação, levando a um encurtamento da estação chuvosa e a um aumento do estresse hídrico, o que pode reduzir a produtividade — estimados em uma queda de 30 kg/ha por dia de redução de duração da estação chuvosa. Diante desses desafios, este estudo explora a irrigação como uma estratégia de adaptação climática, integrando análises regionais de evapotranspiração, vazão de água para irrigação, regionalização de vazões e análise de aptidão do solo. Os resultados indicam que a intensificação através da irrigação é possível sem necessidade do aumento da fronteira agrícola, com mais de 6 milhões de hectares para expansão sob um sistema de gestão outorga coletiva, e quase 2 milhões de hectares sob o sistema atual de outorga. Contudo, limitações na rede de monitoramento de Mato Grosso ressaltam a necessidade de dados de vazão mais confiáveis e de uma gestão robusta para apoiar, de forma sustentável, a expansão de longo prazo da irrigação.

Palavras-chave: irrigação; mudanças climáticas; dupla safra; estresse hídrico; intensificação

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SUMMARY

1. INTRODUCTION

Mato Grosso is a key player in Brazil's agricultural sector, particularly in producing soybeans, maize, and cotton. The state holds 12.7 million hectares of soybeans cropland (IMEA, 2024), mostly rainfed, with approximately only 135,000 hectares currently irrigated using center pivot (ANA, 2021). In the 2023/2024 season, Mato Grosso produced 39 million tons of soybeans (IMEA, 2024). A second crop often follows soybeans. Seven million hectares were planted with maize as a second crop, achieving an average yield of 7,008 kg per hectare (IMEA, 2024), while cotton, also grown as a second crop on 1,5 million hectares, yielding 4,367 kg per hectare (IMEA, 2024). In response to increasing demand and to sustain growth in agricultural production, the state is projected to expand its soybean planted area by 1.5% in the 2024/2025 season (Lennon, 2024).

Climate change poses a significant threat to Mato Grosso's rainfed agricultural systems. Projected temperature increases and reduced rainfall endangering crop yields, with soybean and maize particularly at risk as conditions approach crops' temperature tolerance limits (Zhang, et al., 2021; Bigolin, et al., 2024). The rising global temperatures intensify evaporation demand, leading to higher vapor pressure deficits that increase water stress and reduce photosynthesis (Li et al., 2023). Mato Grosso is further challenged by a shortened rainy season and shifts in precipitation patterns, potentially reducing the profitability of double-cropping systems (Caruta et al., 2021). Under the SSP5–8.5 scenario, rainfall may decrease further, with the rainy season shortening by 5–15 days over the long term (Moon, et al., 2020; Commar, et al., 2024)

The double cropping model in rainfed agriculture, which depends on a rainy season of at least 200 days, is increasingly jeopardized by climate and land cover changes. Recent studies show an average reduction in the rainy season by 5 to 20 days, alongside more frequent dry spells, regional warming, and decreased evapotranspiration (Leite-Filho, et al., 2020; Commar, et al., 2024).

These changes significantly impact the productivity of the second crop, typically maize, by increasing reliance on limited soil moisture reserves and aggravating water stress. Each day of reduced rainfall is associated with a yield loss of approximately 30 kg/ha (Costa, et al., 2019), underscoring the vulnerability of this agricultural model to shifting climatic conditions and the urgent need for adaptation strategies.

In this context, irrigation emerges as a promising adaptation strategy to climate change. It offers the potential to ensure consistent crop production during dry spells and a shortened rainy season, while also supporting the potential for a third crop and increasing overall yields (ANA, 2021; Viana, et al., 2022). This potential of irrigation to transform agriculture in Mato Grosso is a beacon of hope in the face of climate change challenges.

The Nacional Water Agency (ANA, 2021) projected an expansion of 9.8 million hectares of irrigable land using surface water, emphasizing agricultural and pasture areas and excluding previously granted discharges. Expanding on ANA's work, in this dissertation, I will merge previous studies on regional evapotranspiration and water uptake for irrigation, regionalization of discharge, and land suitability, highlighting potential expansion along important river subbasins, with an uncertainty analysis to enhance data reliability.

This dissertation aims to identify where and by how much irrigation can expand under different water policy scenarios in the state of Mato Grosso, with a detailed focus on the Rio das Mortes basin, considering multiple water use restrictions. The findings of this study, which will be assessed using real irrigation practices with the peak water uptake under the shared system and current policy grants, are crucial for mitigating climate change impacts on agricultural productivity and maintaining a sustainable approach without deforestation.

2. DATA AND METHODS

The study was conducted in the state of Mato Grosso, with a more detailed focus on the Rio das Mortes basin. For the entire state, I estimated the growth of irrigation systems using land use data, state water grants, and surface water availability for 12 subbasins that cover the Mato Grosso territory. This evaluation involved extrapolating data on water uptake for irrigation from the Rio das Mortes basin to make statewide estimates. For the Rio das Mortes basin, I included data on power plant grants and evaluated irrigation growth in a micro basin's discharge regionalization scenario.

2.1. STUDY AREA

The analysis was conducted in the state of Mato Grosso (MT), the most relevant state in agriculture in Brazil, leading three main national agricultural products: soybeans, corn, and beef cattle (Brasil, 2023), and holds more than 28% of the national agricultural production value (IBGE, 2024; IBGE, 2023). Mato Grosso is the third largest state in Brazil, with an area of 903,357 km². It encompasses three main hydrographic basins (Alvares, et al., 2013), the Prata main basin, the Tocantins-Araguaia main basin, and the Amazon main basin, as well as three of the country's main biomes: the Amazon (54.2% of the state´s area), Cerrado (39.1%), and Pantanal (6.8%). According to the Köppen classification, the state of Mato Grosso has two climate types: Am (tropical humid or subhumid climate), located in the north of the state, where annual rainfall ranges from approximately 3,000 mm in the north to around 2,000 mm in the southwest, where the dry winter begins and Aw (tropical climate with a dry winter), predominant in the central region of the state and the Pantanal of Mato Grosso (Alvares, et al., 2013).

In the irrigation scenario, the state has a minor part in the Brazilian irrigation system, holding 6.2% of the total irrigation area in the country. Currently, MT has 135,372 ha of cropland under center pivot irrigation (ANA, 2021).

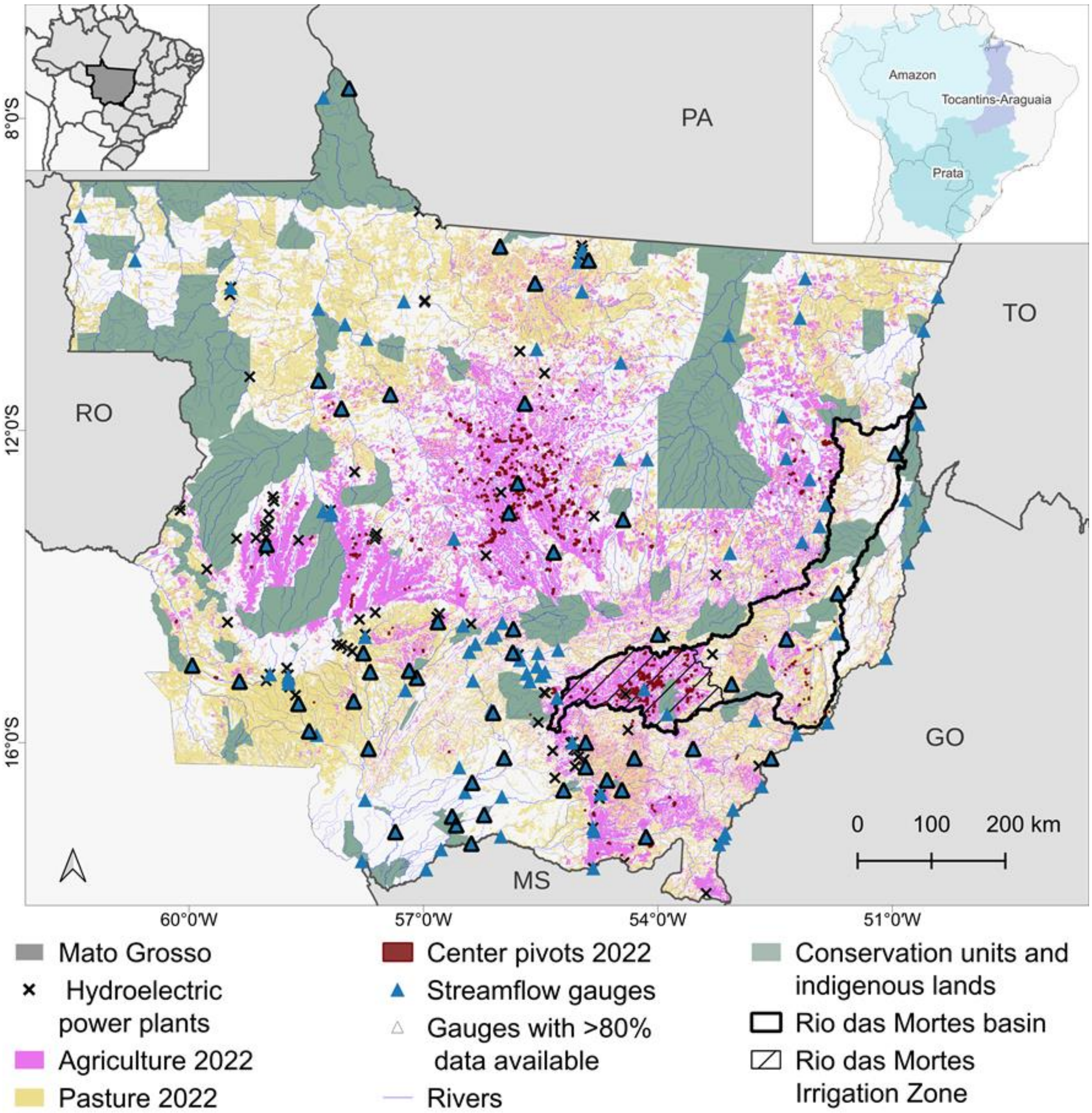

Figure 1. Study area with the hydrography main basins, conservation units, indigenous land, power plants, pasture, and crop area in 2022. The streamflow gauges chosen for the water availability study are delimited in black. The Rio das Mortes basin, used in the case study, and the Rio das Mortes Irrigation Zone, used in the water uptake study, are highlighted.

2.2. SUB BASINS DIVISIONS AND RIVER DISCHARGE DATA

The management of water resources in Brazil is conducted using the hydrographic basin as the unit. In this study, I assessed the use of water resources in the subbasins of the most important rivers in MT. I divided the analyses into two steps. First, I selected 12 river subbasins, with the sum of these areas almost covering the entire state territory and encompassing the three main basins of the Amazon, Prata, and Tocantins-Araguaia (Figure 2 and Table 1).

Table 1. The name, total area (ha) and area of the selected subbasins in MT.

Main Basin		River	Subbasin area in Mato Grosso (ha)	Subbasin total area (ha)
Amazon	(a)	Rio Madeirinha	907,872.92	1,006,629.71
	(b)	Rio Roosevelt	2,897,226.24	4,230,790.00
	(c)	Rio Guariba	1,020,524.05	1,034,674.37
	(d)	Rio Aripuanã	3,820,131.88	3,838,612.64
	(e)	Rio Juruena	17,251,042.58	17,298,187.24
	(f)	Rio Teles Pires	10,241,964.62	10,750,005.48
	(g)	Rio Iriri	737,995.96	1,220,380.00
	(h)	Rio Xingu	16,825,837.66	17,142,830.38
	(i)	Rio Guaporé	3,728,819.61	4,982,090.00
Prata	(j)	Rio Paraguai	17,018,019.96	23,472,233.91
Tocantins-Araguaia	(k)	Rio Araguaia	13,426,702.57	22,659,157.08
	(l)	Rio das Mortes	6,119,932.63	6,119,932.63
		Total	**87,876,138.05**	

Since the main course of the Rio Xingu flows through a protected area, the study adjusted calculations to reflect a more accurate estimate of water availability for potential grants. To achieve this, the total area of the protected region, which measures 3,847,432.33 ha, was deducted from the total area of the Xingu subbasin. This adjustment resulted in a revised subbasin area of 12,295,398.05 ha, providing a more realistic figure for evaluating irrigation potential outside of protected lands.

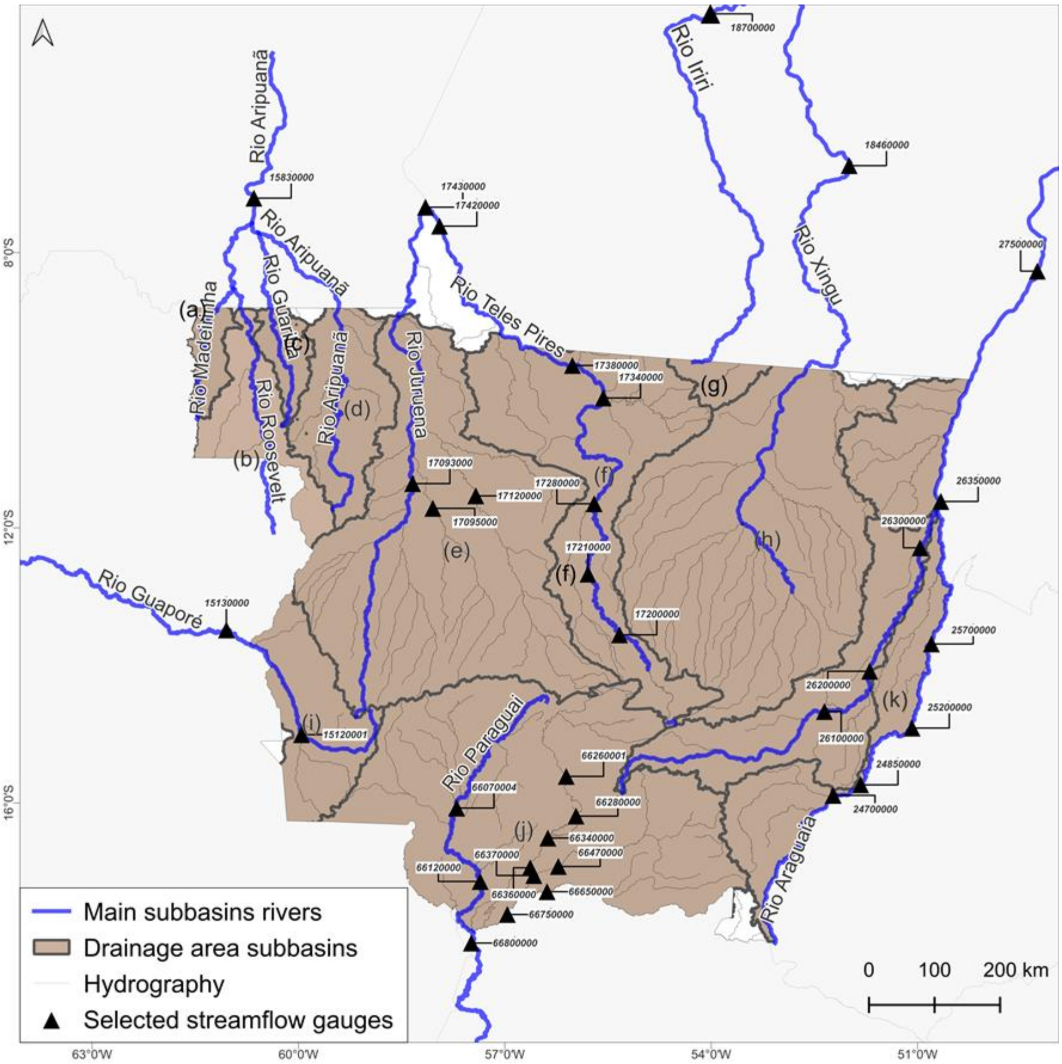

Figure 2. Location of the selected subbasins, hydrography with the main rivers highlighted, and selected streamflow gauges. Amazon: (a) Rio Madeirinha, (b) Rio Roosevelt, (c) Rio Guariba, (d) Rio Aripuanã, (e) Rio Juruena, (f) Rio Teles Pires, (g) Rio Iriri, (h) Rio Xingu, (i) Rio Guaporé; Prata: (j) Rio Paraguai; Tocantins-Araguaia: (k) Rio Araguaia, (l) Rio das Mortes.

Second, after identifying all fluviometric stations within the MT territory, two criteria were posed: (a) data availability: the station needed to have at least 80% data availability from 1990 to 2021, and (b) area criterion: the stations' drainage areas had to cover more than 10% of the subbasin's total drainage area. These were used to ensure the accuracy of the Q_{95} calculation. The nearest station outside the subbasin was also included. Only the Rio Iriri subbasin didn’t fit those two criteria, so the nearest station with more than 50% of data availability was used.

A total of 156 stations were identified, with 64 meeting the 80% data availability criterion and 35 stations meeting both criteria and being used for the Q_{95} calculations. After that, the Q_{95} of each station was determined as the streamflow equaled or exceeded 95% of the time, based on the daily mean streamflow, the station data were provided by the Brazilian Water Agency (ANA, 2024). Figure 2 shows the locations of stations on the main rivers, while Table 2 presents the selected stations and respective station codes, along with their corresponding drainage areas, Q_{95} values, and the percentage of available data at each station.

Table 2. The flow measurement station chosen for the study, divided by the 12 main rivers used, the drainage area of the flow station, which main basin the river belongs to, the selected station for the evaluation, and the percentage of data each chosen station has. Q_{95} is the streamflow that was equaled or exceeded by the daily mean streamflow 95% of the time at each station.

Main Basin		River	Station Code	Station drainage area (km²)	Percentage of data 1990 - 2021	Q_{95} (m³/s)
Amazon	(a)	Rio Madeirinha	15830000	131,000	95.3%	333.8
	(b)	Rio Roosevelt	15830000	131,000	95.3%	333.8
	(c)	Rio Guariba	15830000	131,000	95.3%	333.8
	(d)	Rio Aripuanã	15830000	131,000	95.3%	333.8
	(e)	Rio Juruena	17093000	55,900	95.8%	1,067.3
			17095000	24,700	93.8%	327.9
			17120000	37,100	98.7%	372.0
			17430000	333,000	89.5%	2,897.8
	(f)	Rio Teles Pires	17200000	10,800	96.8%	46.5
			17210000	13,900	84.1%	83.7
			17280000	34,600	84.8%	334.6
			17340000	52,200	90.5%	427.4
			17380000	81,600	86.2%	542.6
			17420000	138,000	85.5%	1,014.1
			17430000	333,000	89.5%	2,897.8
	(g)	Rio Iriri	18700000	122,000	58.3%	155.1
	(h)	Rio Xingu	18460000	210,000	96.1%	670.7
	(i)	Rio Guaporé	15120001	22,500	98.2%	30.2
			15130000	54,400	99.5%	153.4

			66070004	32,400	98.2%	215.0
			66120000	64,000	80.2%	194.7
			66260001	23,500	84.4%	107.4
			66280000	28,900	89.3%	117.7
			66340000	36,900	91.9%	129.7
Prata	(j)	Rio Paraguai	66360000	38,500	90.4%	132.7
			66370000	39,000	94.8%	148.3
			66470000	24,100	88.8%	130.2
			66650000	30,000	84.6%	138.9
			66750000	103,000	89.8%	413.5
			66800000	234,000	86.2%	793.0
			24700000	36,800	98.2%	173.9
			24850000	50,100	98.2%	206.6
			25200000	76300	98.2%	280.2
			25700000	92,300	98.2%	258.1
Tocantins-Araguaia	(k)	Rio Araguaia	26100000	25,300	99.5%	230.0
			26200000	41,100	99.2%	273.8
			26300000	59,300	98.4%	319.3
			26350000	194,000	99.0%	638.9
			27500000	332,000	99.7%	726.2
	(l)	*Rio das Mortes**	-	-	-	*417.6*

**See case study.*

2.3. WATER USE GRANTED DISCHARGE DATA

To quantify the amount of discharge already used in the subbasins and to avoid expanding irrigation in areas with lower water availability, I utilized the surface water use granted discharges provided by ANA (2024), National Registry of Water Resources Users (CNARH). These sources provide comprehensive information about the geographic location of the grant, river source, the amount of granted discharge and the purpose of the use for the grant. The grants are divided into consumptive uses (industrial use, irrigation, and human consumption) and non-consumptive uses (using water without consumption), including recreation, fishing, and hydropower production. All the grants were analyzed, but those with expiration dates until 2022 were excluded. The groundwater granted discharges were not used in this study.

2.4. WATER UPTAKE FOR IRRIGATION AND ACTUAL IRRIGATED AREA DATA

To quantify the water used by irrigation in the state, I used the dataset produced by Santos (2024). The dataset contains the irrigation depth for each center pivot mapped in the Rio das Mortes basin, calculated using two remote sensing products of evapotranspiration data: Global Daily Evapotranspiration (GLODET) project database and MOD16A2GF Version 6.1 Evapotranspiration/Latent Heat Flux (ET/LE) product.

The MOD16A2GF product is derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor onboard the Terra satellite. Its algorithm logic is based on the Penman-Monteith equation. GLODET is a free platform hosted by the Daugherty Water for Food Global Institute (DWFI) at the University of Nebraska. The data are computed using the two-source energy balance model ALEXI (Atmosphere-Land Exchange Inverse) developed by the Agricultural Research Service of the U.S. Department of Agriculture (GloDET, 2024).

I proceeded with the analysis using data derived from ALEXI over MODIS because the MODIS data showed lower values, leading to an underestimation of water use. Using ALEXI data, water demand is higher, and the potential growth assessment is more conservative.

As the Rio das Mortes is the most important area of irrigated cropland and the most intensive irrigation area in the state, I used historical data on water uptake for irrigation and the effectively irrigated area to assess the growth for the entire state, based on the Rio das Mortes pattern, aiming to optimize water utilization while conservatively calculating the potential for expansion, thereby minimizing possible future regional water conflicts (calculation described in Section 2.6).

2.5. COMPUTATION OF MATO GROSSO WATER AVAILABILITY

To assess Mato Grosso's water availability, I estimated the Q_{95} in the subbasins by averaging the Q_{95} values of all stations within or closest to the subbasin's drainage area (Table 1, Figure 2), using the drainage area ratio method (Chaves, et al., 2002; Stedinger, et al., 1992) as shown in Equation 1. The drainage area ratio method infers that the reference flow at point y will be proportional to the ratio between the upstream areas of points x and y.

$$Q_y = \left(\frac{A_y}{A_x}\right) \times Q_x \tag{1}$$

Where Q_y is the unknown flow at any upstream point of the subbasins, Q_x is the reference flow at the gauging station, A_y and A_x are the drainage areas relative to the point of unknown flow and the station, respectively.

This method was chosen since it is an interpolative method, it does not require the definition of hydrologically homogeneous regions and allows an estimate of the uncertainty of the water availability in the state.

2.6. COMPUTATION OF THE POTENTIAL GROWTH OF IRRIGABLE AREA

Based only on water availability, the potential growth of the irrigable area in MT was calculated using two different methodologies: first, using the sum of valid irrigation grants in the state (Section 2.3) and effectively irrigated area (Section 2.4). This method mimics the current water resource management policy, based on individual water use grants.

The second method uses actual water uptake for irrigation, assessed using remote sensing, and effectively irrigated areas (Section 2.4). This method allowed the estimation of the expansion of irrigable areas as if water was granted collectively to the farmers, using a shared management system. In the latter case, the maximum rate of irrigation depth found in the time series was used as a benchmark of collective water use by farmers. This estimation focused on finding the highest flow value used to irrigate one hectare of land, the maximum specific irrigation flow rate (q_{imax}).

Two flow rates were calculated: $q_{imaxshared}$, under the shared management system, and $q_{imaxcurrent}$ based on current water resource management. Both flow rates were calculated using the same method, as shown in Equation 2:

$$q_{imax} = \frac{Q_{maxirrigation}}{A_{irrigated}} \qquad (2)$$

Where q_{imax} is the maximum specific irrigation flow rate (m^3/s.ha), $Q_{maxirrigation}$ is the discharge either granted or effectively used for irrigation (m^3/s), and $A_{irrigated}$ is the effectively irrigated area (ha).

For $q_{imaxshared}$, using data from Section 2.4, I divided the monthly peak water uptake for irrigation (from the historical series of 2001 to 2022) by the corresponding irrigated area during the peak year. This conservative approach was chosen to reduce the potential expansion area and minimize potential water conflicts in the region so that irrigation growth does not lead to water scarcity.

For $q_{imaxcurrent}$, I divided the Rio das Mortes into 10 regions, each having similar irrigation grants and irrigated areas. I then calculated $q_{imaxcurrent}$ for each region, by dividing the total valid irrigation grants in that region (m^3/s) by the effectively irrigated area of the region (ha) for 2022 in each region. Then, I averaged the results to obtain a representative value (Figure 3).

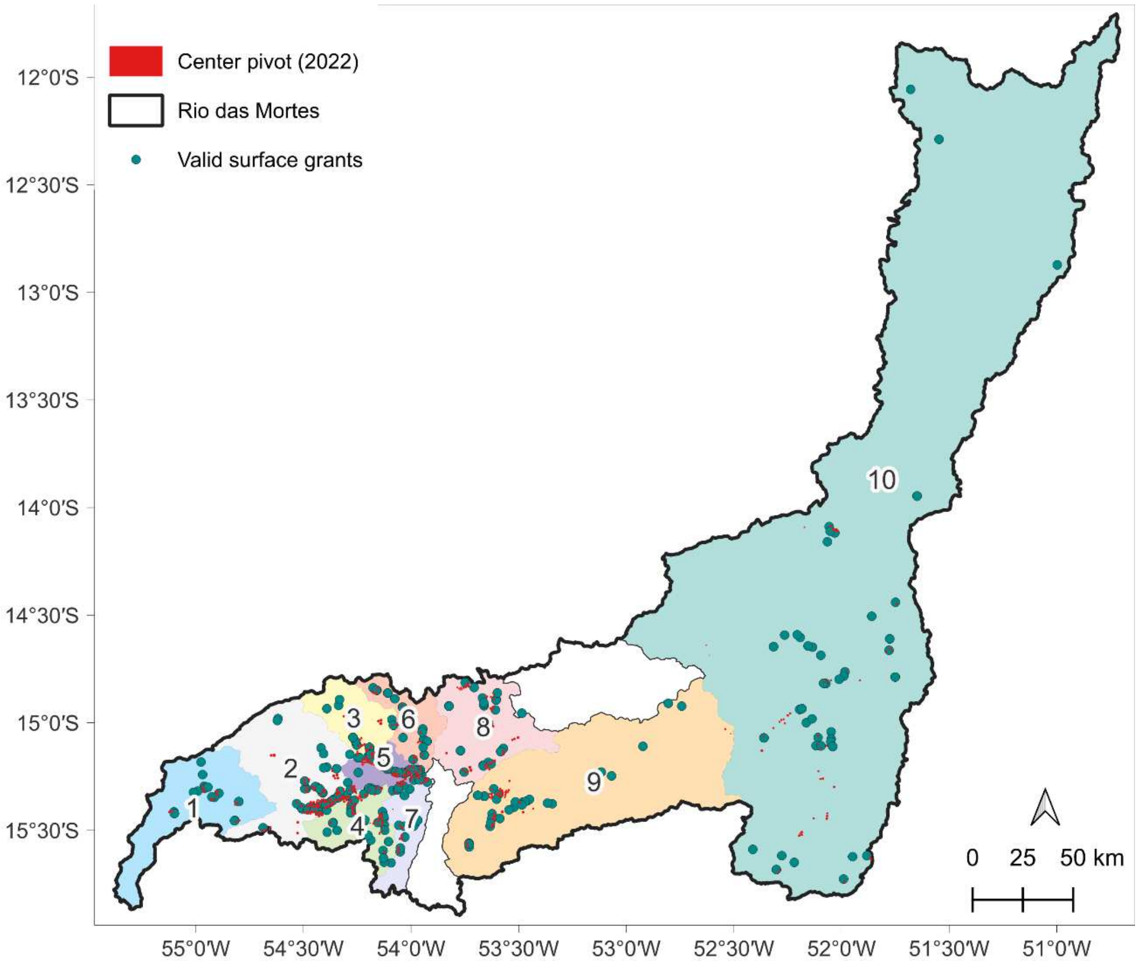

Figure 3. Division of Rio das Mortes to calculate $q_{imaxcurrent}$.

Afterward, in addition to water availability, I considered legal regulations to estimate the potential growth of irrigable areas in MT. According to the Mato Grosso state regulations (SEMA, 2007), 70% of the Q_{95} flow of rivers can be used for consumptive purposes. This ensures compliance with legal water usage limits and promotes sustainable water management practices.

To assess the amount of land that can be further irrigated, I deducted the water already allocated through valid grants in the state. This ensures that water reserved for non-irrigation purposes remains dedicated to that purpose, preventing diversion and ensuring adequate water availability for all users.

After establishing the available water quantity, I calculated the potential growth of irrigable areas using Equation 3, which involves dividing the available water quantity by the maximum specific irrigation flow rate from the two perspectives (q_{imax}). This approach ensures that irrigation activities operate within legal limits, minimizing the risk of water scarcity and encouraging responsible water use practices.

$$A_{max} = \frac{70\%Q_{95} - Q_{grant}}{q_{imax}} \tag{3}$$

Where A_{max} is the potential growth of irrigable area (ha), Q_{grant} is the subbasins discharge of water already granted by Mato Grosso (m^3/s).

2.7. IRRIGATION LAND SUITABILITY – DATA AND METHODS

In this section, I estimate the potential growth of irrigable land based on the availability of suitable areas within the state of MT. The evaluation considers land suitability criteria, including slope, land use, and proximity to rivers. Specifically, land must have a slope of less than 5% to ensure the viability of implementing irrigation systems without incurring excessive costs. To prevent further deforestation, the expansion of irrigable areas is limited to regions currently utilized for agriculture or pasture, avoiding the conversion of native vegetation into new cropland. Additionally, suitable land must be located within 10 kilometers of a river to facilitate effective water withdrawal.

For the slope map, I used the data derived from Shuttle Radar Topography Mission (SRTM) elevation data (Farr, et al., 2007), at a spatial resolution of 30 × 30 meters. For the land use map, I used the year 2022 obtained from Collection 8 of the MAPBIOMAS project, at a spatial resolution of 30 × 30 meters, through pixel-by-pixel classification of LANDSAT images using the Random Forest classifier (Souza Jr, et al., 2020). The river data from the National Water Agency (ANA, 2018) to determine distances up to 10 kilometers from them. Only rivers with lengths greater than 10 kilometers were considered for this analysis.

The selection of areas suitable for irrigated agriculture followed the flowchart below (Figure 4). This resulted in four possible classifications: restricted or wetlands, suitable for irrigation and presently under agriculture and/or pasture, suitable for irrigation and presently under native vegetation, and unsuitable for irrigation.

For the restricted or wetlands classification, I identified the protected areas of Mato Grosso, including legal reserves (RL) and permanent preservation areas (APP) obtained from the Rural Environmental Registry (CAR) (www.car.gov.br). Also, data on conservation units (UC) and indigenous lands (TI) from the Terrabrasilis platform (Assis, et al., 2019). This category includes areas such as mangroves, floodable forests, wooded sandbank vegetation, and herbaceous sandbank vegetation or wetlands, which are not eligible for irrigation expansion.

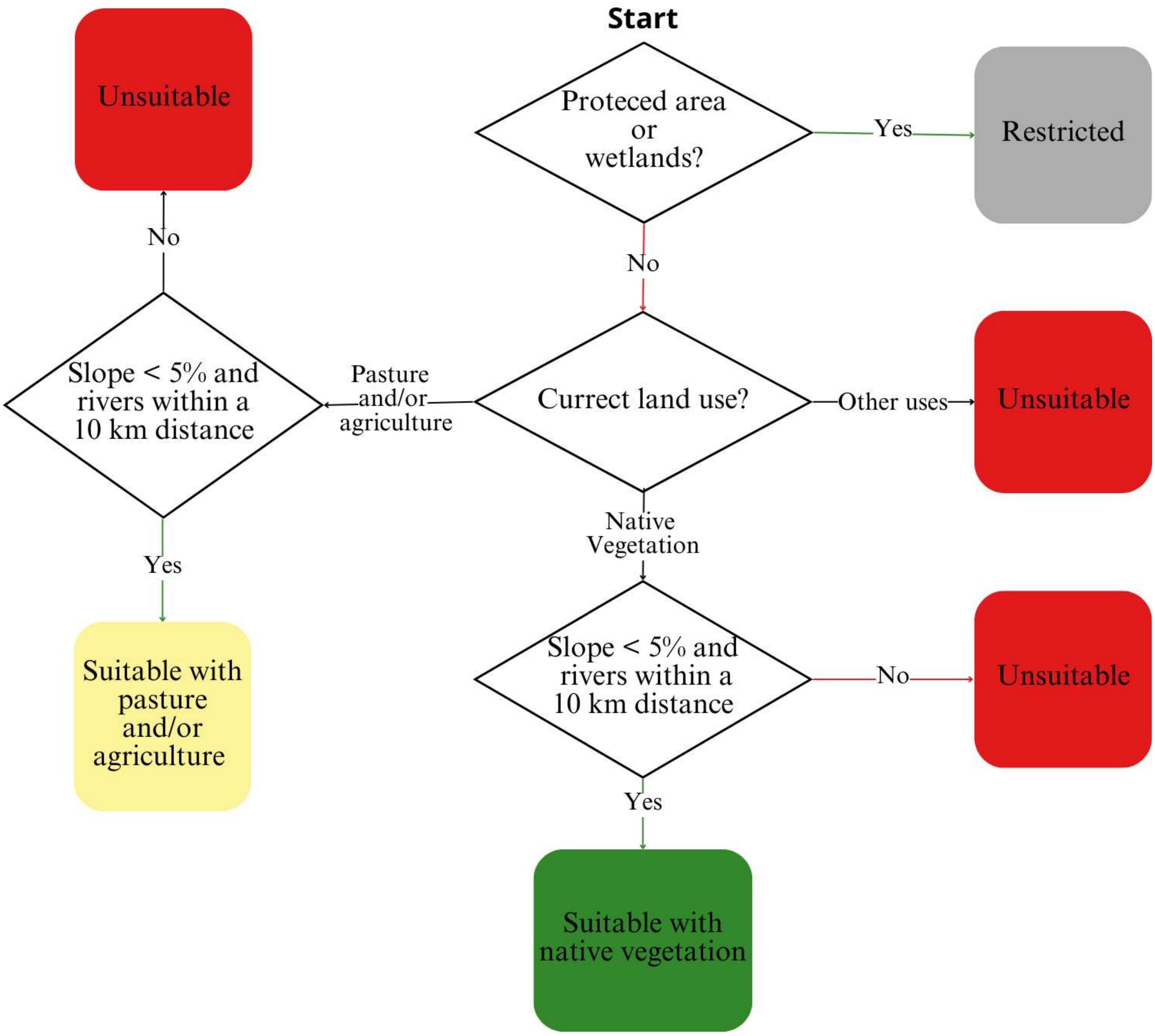

Figure 4. Flowchart for irrigated agriculture land suitability.

Suitable areas comply with criteria of slopes less than 5% and proximity within 10 km of rivers. Lands already used for agriculture are classified as suitable for irrigation and are presently under agriculture and/or pasture. In contrast, lands with native vegetation are classified as suitable for irrigation and presently under native vegetation. Areas that do not meet the slope or river distance criteria, or have other land uses, such as water bodies and non-vegetated areas, are classified as unsuitable.

2.8. CASE STUDY - RIO DAS MORTES

This section presents the methodology for a comprehensive assessment of irrigation as a strategy for adapting agriculture to climate change in the Rio das Mortes Basin. In addition to the state-wide analysis, which analyzed data on land suitability and water grants, this case study includes a detailed analysis that uses discharge regionalization data by microbasin and considers water reservations allocated for energy production by hydroelectric power plants.

2.8.1. DISCHARGE REGIONALIZATION

The Q_{95} flow along all river segments within the Rio das Mortes subbasin was estimated based on the methods of Eletrobrás (1985), Rodriguez (2008), and Pruski et al. (2013). The Rio das Mortes subbasin was divided according to the Ottocoded Hydrographic of ANA. Those methods define hydrologically homogeneous regions and establish regression equations between flow and physical and climatic variables, such as drainage area and annual precipitation. 59 streamflow stations and 225 rainfall stations were selected for this analysis. Linear and potential regression models were evaluated, prioritizing those with the lowest residuals at the streamflow stations closest to the Rio das Mortes. Additionally, a physical behavior analysis was conducted to ensure the results approximated the observed values. The equations are included in Appendix A.

2.8.2. NON-CONSUMPTIVE WATER GRANTED TO HYDROPOWER PLANTS

This section provides detailed insight into reserving water for energy production, which involves collaboration between the National Agency of Electric Energy (ANEEL) and the National Water Agency (ANA). ANA emits the Declaration of Reservation of Hydrological Availability (DRDH) to ANEEL, granting permission to utilize hydroelectric energy potential. Once the energy company receives the concession or authorization from ANEEL, the DRDH is converted into a water use rights grant. This grant authorizes the concession or authorization holder to use water resources for energy production. The water uses rights grant, following the DRDH period, will last 35 years and can be extended by ANA (ANA, 2024).

The DRDH establishes two types of discharge reservations, or provisions, to manage water flow upstream of power plants. The first reservation sets apart water for consumptive uses, including urban and rural water supply, irrigated agriculture, manufacturing, mining, and thermoelectric power generation. These allocations are based on flow estimates provided by the State Environmental Agency (SEMA) and the National Water Agency (ANA). The second reservation ensures that minimum flows are maintained in water bodies to protect ecological balance. After fulfilling these restrictions, the remaining water constitutes the flow available for hydroelectric power generation.

In this analysis, I examined the state decrees to detect possible limitation factors of expanding irrigated agriculture, primarily due to water allocations prioritized for hydroelectric energy production purposes. Figure 4 displays each hydroelectric power plant's geographical position and operational status. A summary of the information on the power plants is presented below. More detailed information on each project, including discharge reservations, is presented in Appendix B.

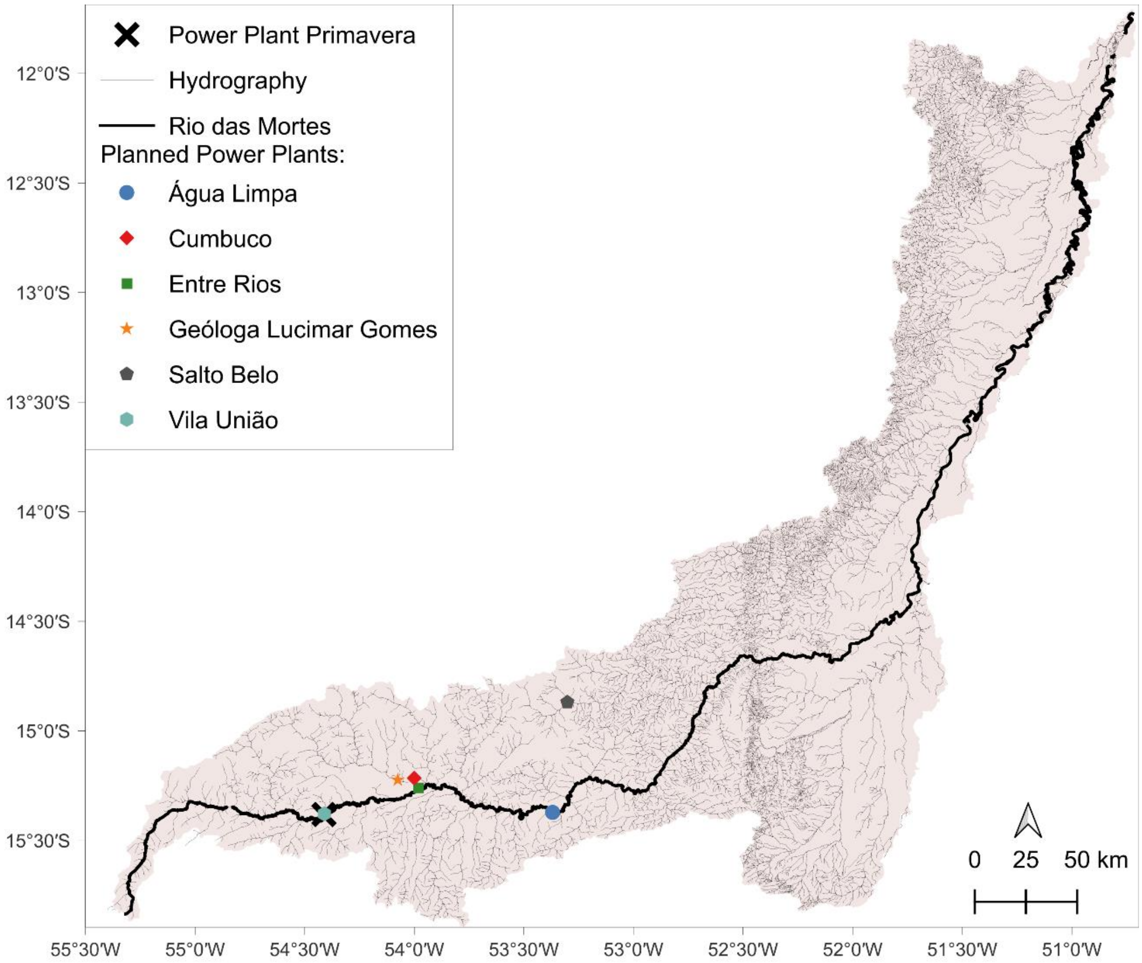

Figure 5. Location of the operational and planned power plant in Rio das Mortes basin.

The Rio das Mortes basin currently hosts one operational hydropower plant, Primavera, located along the main stem of the Rio das Mortes, with an installed capacity of 11.80 MW. The decree does not specify the water reserved for this plant. Additionally, six hydropower projects — Água Limpa, Cumbuco, Entre Rios, Geóloga Lucimar Gomes, Salto Belo, and Vila União — are at various stages of development.

Among the non-operational plants along the main course of the Rio das Mortes, the Água Limpa hydropower plant was regulated by Decree Nr. 119 of July 15, 2010, valid until June 26, 2022. The Vila União plant, governed by Decree Nr. 898 of October 20, 2022, is valid until October 30, 2025, and is expected to produce 18 MW.

On the Rio Cumbuco, a tributary of the Rio das Mortes, the Cumbuco plant is regulated by Decree Nr. 985 of November 18, 2022, with a potential capacity of 17 MW. The decree is valid until November 30, 2024, with a possible three-year renewal. The Geóloga Lucimar Gomes plant, under Decree Nr. 720 of September 1, 2022, is valid until August 31, 2025, and has an expected capacity of 18 MW.

The Salto Belo plant, located on the Rio Noidore, another tributary, is regulated by Decree Nr. 133 of February 28, 2022, valid until June 26, 2022.

An additional hydropower plant, Entre Rios, is planned along the main course of the Rio das Mortes but has yet to receive a Declaration of Reservation of Hydrological Availability.

2.8.3. RIO DAS MORTES SCENARIOS EVALUATION

First, using regionalized discharge data for the Rio das Mortes and its suitability classification, the water-limited potential irrigable area was recalculated based on the region's specific suitability patterns. To avoid superposition, the basin was divided into smaller zones to obtain a more realistic estimate of water-limited potential irrigation growth, excluding large contiguous areas classified as restricted or wetlands.

Next, I analyzed water use in more detail at the micro-basin level, specifically within the Rio das Mortes Irrigation Zone. This involved cross-referencing spatial data on water grants, peak water uptake per irrigation pivot from 2001 to 2022 and assessing water stress in the basin using regionalized water availability equations to assess whether, on a smaller scale such as a micro basin, Rio das Mortes can maintain a sustainable irrigation growth scenario. The analysis only considered the functional power plant because of the current water-use scenario in the Rio das Mortes basin.

The plant's water use was excluded, as it is non-consumptive and does not remove water from the system.

To evaluate water use and availability comprehensively, I conducted three assessments: (i) the ratio of total surface water grants to Q_{95}, (ii) water uptake for irrigation relative to irrigation water grants, and (iii) water uptake for irrigation relative to Q_{95}. These assessments help identify the sustainability and potential limitations of water use in the basin.

3. RESULTS

The results section is divided into Mato Grosso's assessment and the Rio das Mortes case study.

3.1. MATO GROSSO ASSESSMENT

3.1.1. WATER AVAILABILITY

Table 3 shows the mean and confidence interval ($\alpha = 0.05$) of the estimated Q_{95} and the amount of water use allowed by state law (70% Q_{95}), the sum of the surface water grants (Q_{grants}), the sum of the surface water grants for irrigation ($Q_{grantsirrigation}$), and the remaining flow still not granted ($70\%Q_{95}$ - Q_{grant}).

Firstly, Mato Grosso (MT) has 453.327 m^3/s of surface water already allocated through water grants. Of this, 398.868 m^3/s is for irrigation purposes, representing 82% of the total water grants (Table 3). This indicates the importance of irrigated agriculture in the state.

Table 3. Mean estimated Q_{95} with a 95% confidence interval, the amount of water use allowed by state law (70% Q_{95}), the sum of the surface water grants (Q_{grants}), the sum of the surface water grants for irrigation ($Q_{grantsirrigation}$) and the remaining flow still not granted ($70\%Q_{95} – Q_{grant}$).

	River	Q_{95} (m^3/s)	70% Q_{95} (m^3/s)	Q_{grant} (m^3/s)	$Q_{grantsirrigation}$ (m^3/s)	$70\%Q_{95}$ – Q_{grant} (m^3/s)
(a)	Rio Madeirinha	25.65 (n = 1)	17.95 (n = 1)	0.01	0.01	17.94 (n = 1)
(b)	Rio Roosevelt	107.80 (n = 1)	75.46 (n = 1)	0.00	0.00	75.46 (n = 1)
(c)	Rio Guariba	26.36 (n = 1)	18.45 (n = 1)	0.00	0.00	18.45 (n = 1)
(d)	Rio Aripuanã	97.81 (n = 1)	68.46 (n = 1)	0.33	0.05	68.14 (n = 1)
(e)	Rio Juruena	2,209.68± 784.87 (n = 4)	1,546.78± 549.41	89.49	87.87	1457.28± 549.41

			(n = 4)			(n = 2)
(f)	Rio Teles Pires	781.41± 143.18 (n = 7)	546.99± 100.23 (n = 7)	78.97	71.11	468.02± 100.23 (n = 7)
(g)	Rio Iriri	15.51 (n = 1)	10.86 (n = 1)	0.00	0.00	10.86 (n = 1)
(h)	Rio Xingu	424.63 (n = 1)	297.24 (n = 1)	105.76	105.02	191.49 (n = 1)
(i)	Rio Guaporé	103.65± 72.21 (n = 2)	72.55± 50.55 (n = 2)	22.70	21.73	49.85± 50.55 (n = 2)
(j)	Rio Paraguai	992.71± 145.07 (n = 11)	694.90± 101.55 (n = 11)	56.00	24.00	638.90± 101.55 (n = 11)
(k)	Rio Araguaia	1,055.84± 317.90 (n = 9)	739.09± 222.53 (n = 9)	99.73	89.04	639.36± 222.53 (n = 9)
(l)	Rio das Mortes*	417.64	292.35	85.87	82.45	187.39
Mato Grosso total		-	-	**453.33**	**398.87**	-

**Rio das Mortes' values are included in the Rio Araguaia's total.*

Additionally, Table 3 displays each subbasin's estimated Q_{95} values and corresponding water grants. The Q_{95} values for MT's subbasins ranged from 1,808.98 m^3/s to 15.51 m^3/s, reinforcing that the state has abundant water resources. The subbasin with the highest flow rate is the (e) Rio Juruena, with 2,209.68± 784.87 m^3/s. Other subbasins also presented high water potentials, such as the (j) Rio Paraguai (992.71± 145.07 m^3/s), (f) Rio Teles Pires (781.41± 143.18 m^3/s), (h) Rio Xingu (424.63 m^3/s) and (l) Rio das Mortes (417.64 m^3/s).

For water granted, I found that (h) Rio Xingu had the highest amount of granted water, with 105.76 m^3/s. (k) Rio Araguaia presented 99.73 m^3/s of granted water, of which 85.87 m^3/s is in (l) Rio das Mortes. (e) Rio Juruena (89.49 m^3/s), (f) Rio Teles Pires (78.97 m^3/s), (j) Rio Paraguai (56.00 m^3/s), and (i) Rio Guaporé (22.70 m^3/s) also showed significant amounts of granted water. In contrast, (a) Rio Madeirinha, (b) Rio Roosevelt, (c) Rio Guariba, and (d) Rio Aripuanã did not have significant water grants (Table 3).

On a subbasin scale, no subbasin exceeded the limits set by state law, indicating no water conflicts so far. On average, subbasins granted 9% of the state's allowable limit. The Rio Juruena shows the greatest potential for increasing water grants, as it utilizes only 13% of the state's limit, despite having the highest Q_{95} (Table 3). In contrast, the Rio Xingu, Rio Guaporé, and Rio das Mortes have the highest percentages of water already granted, at 35%, 30%, and 28% respectively. Other sub-basins have granted less than 13% of their water resources.

The results of Table 3 also showed that some river subbasins have significant amounts of water grants for irrigation purposes. They include (h) Rio Xingu (105.02 m^3/s), (k) Rio Araguaia (89.04 m^3/s) with (l) Rio das Mortes contributing to 82.45 m^3/s of the total, (e) Rio Juruena (87.87 m^3/s), (f) Rio Teles Pires (71.11 m^3/s), and (i) Rio Guaporé (21.73 m^3/s). In contrast, (j) Rio Paraguai had the lowest water grants percentage for irrigation, with 24.00 m^3/s, representing 43% of the total grants. Notably, the Rio Paraguai is the only subbasin where more water is granted for uses other than irrigation, in all other subbasins with significant grants, nearly all the water is allocated for irrigation purposes.

3.1.2. POTENTIAL GROWTH OF IRRIGABLE AREA

First, I calculated the potential growth of irrigable area considering current water grant practices, the valid irrigation grants (m^3/s) were determined for each of the 10 subdivisions of the Rio das Mortes basin, as shown in Table 4 and illustrated in Figure 3. Using the irrigated area for 2022, the average maximum specific irrigation flow rate

($q_{imaxcurrent}$) across these subdivisions was calculated as 2.20×10^{-3} m³ s⁻¹ ha⁻¹, with a 95% confidence interval of $\pm 0.58 \times 10^{-3}$ $m^3\ s^{-1}\ ha^{-1}$ and n = 10 (2.20±0.58 L/s/ha).

Table 4. Calculated pivot area (ha), values of maximum specific irrigation flow rate ($q_{imaxcurrent}$, $m^3\ s^{-1}\ ha^{-1}$), for Rio das Mortes division.

Division	Irrigated area (ha)	Valid irrigation grants (m³/s)	$q_{imaxcurrent}$ ($m^3\ s^{-1}\ ha^{-1}$)
1	1,811.06	2.55	0.0014
2	9,162.48	17.16	0.0019
3	2,275.64	10.61	0.0047
4	4,722.10	10.87	0.0023
5	3,896.25	7.57	0.0019
6	1,812.90	5.75	0.0032
7	1,435.72	3.95	0.0028
8	5,118.09	12.54	0.0024
9	4,159.61	10.80	0.0026
10	4,222.36	17.74	0.0042
	38,616.21		**0.0022 ± 0.000582**

Second, I calculated the potential growth of irrigable areas considering shared water resources. The monthly peak water demand for irrigation in Rio das Mortes was about 17 m³/s, which occurred in 2018 over an area of 34,175 hectares. Using this data, the maximum specific irrigation flow rate under the shared management system ($q_{imaxshared}$) is estimated at 4.97×10^{-4} m³/s per ha (0.497 L/s/ha, or about 23% of the average amount granted).

Furthermore, Table 5 presents the calculation of the potential growth of irrigable areas limited by water availability and divides it into the two water management criteria described above. The land suitable for irrigation in each subbasin is also shown for comparison.

Table 5. Mean calculated values of current and shared management system water-limited irrigation growth potential (ha) with a 95% confidence interval, and values of land suitability for irrigation per river subbasin.

River subbasin		Water limited irrigation growth potential (ha)		Land Suitability for irrigation (ha)
		Shared management method	Valid irrigation grants method	
(a)	Rio Madeirinha	36,066 (n = 1)	9,343 ± 2,083 (n = 10)	32,265
(b)	Rio Roosevelt	151,696 (n = 1)	39,300 ± 8,762 (n = 10)	74,034
(c)	Rio Guariba	37,098 (n = 1)	9,611 ± 2,143 (n = 10)	40,969
(d)	Rio Aripuanã	136,981 (n = 1)	35,487± 7,912 (n = 10)	280,641,00
(e)	Rio Juruena	2,587,641 ± 1,444,939 (n = 4)	670,381 ± 131,115 (n = 40)	3,502,626
(f)	Rio Teles Pires	940,857 ± 201,489 (n = 7)	243,748 ± 25,491 (n = 70)	2,691,160
(g)	Rio Iriri	21,828 (n = 1)	5,654 ± 1,260 (n = 1)	90,028
(h)	Rio Xingu	384,942 (n = 1)	99,727 ± 22,236 (n = 10)	3,619,426
(i)	Rio Guaporé	100,218 ± 101,614 (n = 2)	25,963 ± 7,523 (n = 20)	867,446
(j)	Rio Paraguai	1,284,368 ± 204,146 (n = 11)	332,742 ± 27,221 (n = 110)	3,530,431
(k)	Rio Araguaia	1,285,294 ± 671,017 (n = 9)	332,982 ± 43,651 (n = 90)	3,091,971
(l)	Rio das Mortes*	415,027 (n = 1)	107,535 ± 23,978 (n = 10)	1,761,782
State Total		**6,376,076 ± 1,727,727**	**1,912,478 ± 303,381**	**17,820,975**

*Rio das Mortes' values are included in the Rio Araguaia's total.

Under the shared management system, the water-limited potential for irrigation growth across the assessed subbasins is 6,376,076 ± 1,727,727 ha. Under the current management system, however, this potential is reduced to 1,912,478 ± 303,381 ha.

Across the entire state of MT, 17,820,975 ha of land meets the suitability criteria for irrigation as outlined in Section 2.7.

The water-limited irrigation potential varied significantly across the subbasins. (g) Rio Iriri exhibited the lowest potential for irrigation expansion in both systems, the shared management system (21,828 ha) and the current management system (5,654 ± 1,260 ha), despite having a substantial area suitable for irrigation (90,028 hectares). In contrast, (c) Rio Guariba showed a water-limited potential in the shared management system of 37,098 ha, nearly matching its calculated land suitability for expansion (40,969 hectares). However, under the current management system, the potential growth in (c) Rio Guariba was significantly reduced to 9,611 ± 2,143 ha.

(d) Rio Aripuanã demonstrated higher water-limited potentials, with 136,981.16 ha under the shared management system and 35,487 ± 7,912 ha under the current management system, alongside extensive areas suitable for irrigation totaling 280,641 ha. Meanwhile, (i) Rio Guaporé showed considerable variability, with confidence intervals exceeding the average potential values under the shared management system. Specifically, its water-limited potential under the shared management system was 100,218 ± 101,614 ha, while under the current management system, it was 25,963 ± 7,523 ha. Furthermore, (i) Rio Guaporé also had a large area suitable for irrigation of 867,446 ha (Table 4).

Table 4 also showed that the water-limited potential under the shared management system exceeded land suitability only in (a) Rio Madeirinha and (b) Roosevelt. In (a) Rio Madeirinha, the water-limited potential for expansion was 36,066 ha, while the suitable land for expansion was 32,265 ha. Similarly, in (b) Rio Roosevelt, 151,696 ha of water-limited potential was available for expansion, compared to 74,034 ha of suitable land. However, this pattern did not hold under the current management system. In this scenario, (a) Rio Madeirinha and (b) Rio Roosevelt had reduced water-limited potentials of 9,343 ± 2,083 ha and 39,300 ± 8,762 ha, respectively.

Additionally, (h) Rio Xingu, (f) Rio Teles Pires, and (j) Rio Paraguai show significant water-limited growth potentials under the shared management system, with values of 384,942 ha, 940,857 ± 201,489 ha, and 1,284,368 ± 204,146 ha, respectively. However, in the current management system, these potentials decrease notably to 99,727 ± 22,236 ha, 243,748 ± 25,491 ha, and 332,742 ± 27,221 ha. These subbasins also have even larger areas available for expansion, at 3,619,426 ha, 2,691,160 ha, and 3,530,431 ha, respectively, with (h) Rio Xingu offering the greatest area suitable for irrigation expansion (Table 4).

Finally, (k) Rio Araguaia displayed a water-limited irrigation growth potential of the shared management system of 1,285,294 ± 447,345 ha, the current management system of 332,982 ± 43,651 ha, and 3,091,971 ha of land suitable for irrigation. Within this total, (l) Rio das Mortes contributes 415,027 ha of water-limited irrigation growth potential in the shared system, 107,535 ± 23,978 ha in the current system, and 1,761,782 hectares of land suitable for irrigation (Table 4).

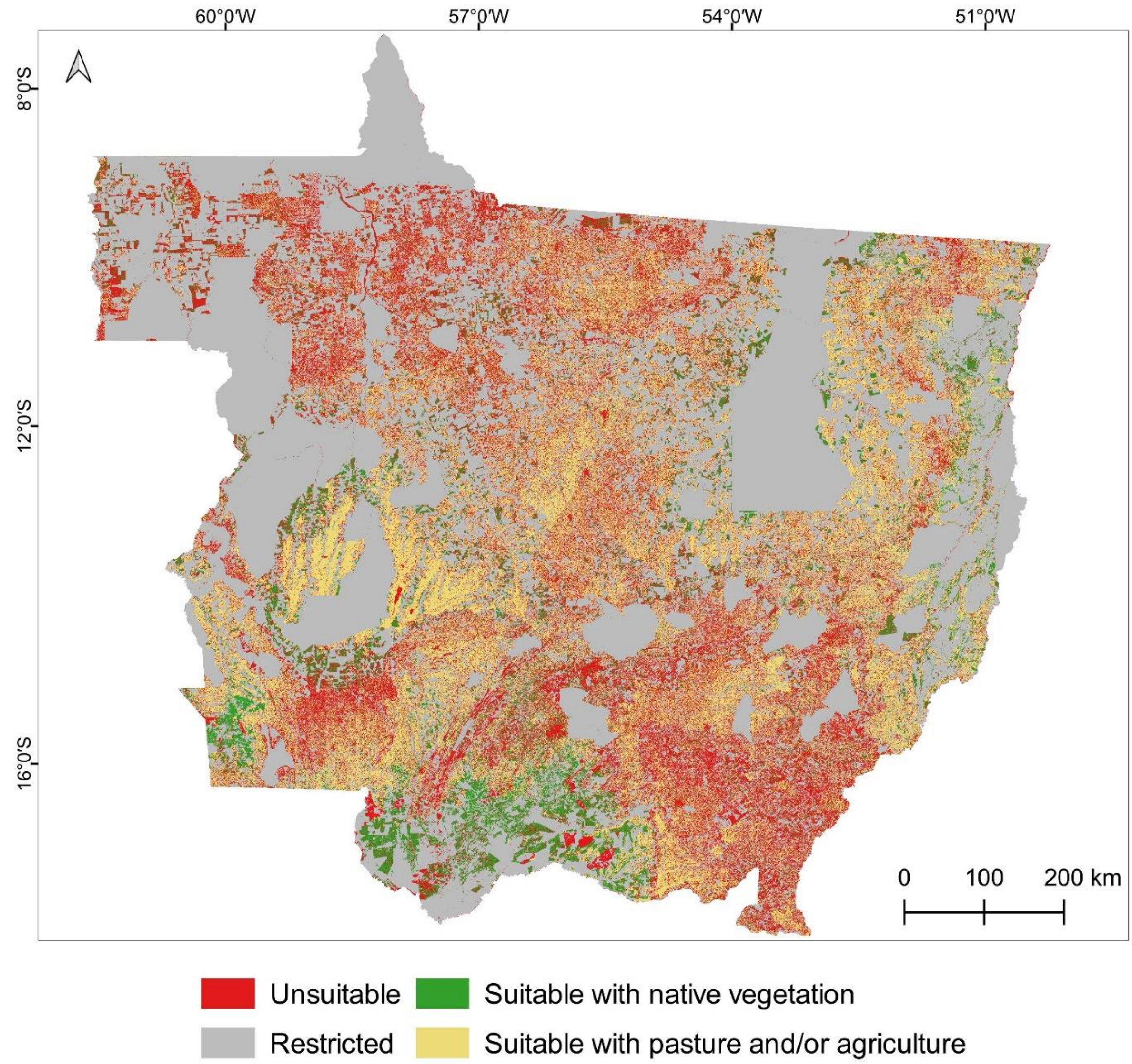

Figure 6. The suitability for irrigation of the state of Mato Grosso is divided into 4 classes: unsuitable (red), restricted (gray), suitable with native vegetation (green), and suitable with pasture and/or agriculture (yellow).

3.2. RIO DAS MORTES CASE STUDY

This section presents the results of the Rio das Mortes basin in more detail.

3.2.1. RIO DAS MORTES WATER AVAILABILITY

Figure 6 displays the estimated flows along all river segments by the discharge regionalization and the water use allowed by MT's law per micro basin.

The streamflow gauges calculated Q95 values of 72.9 m³/s and 205.6 m³/s, as shown in Figure 6. In the main course of the Rio das Mortes basin, the Q_{95} ranges from 20.7 m³/s to 417.6 m³/s. Figure 7 also illustrates the hydrological potential of the Rio das Mortes.

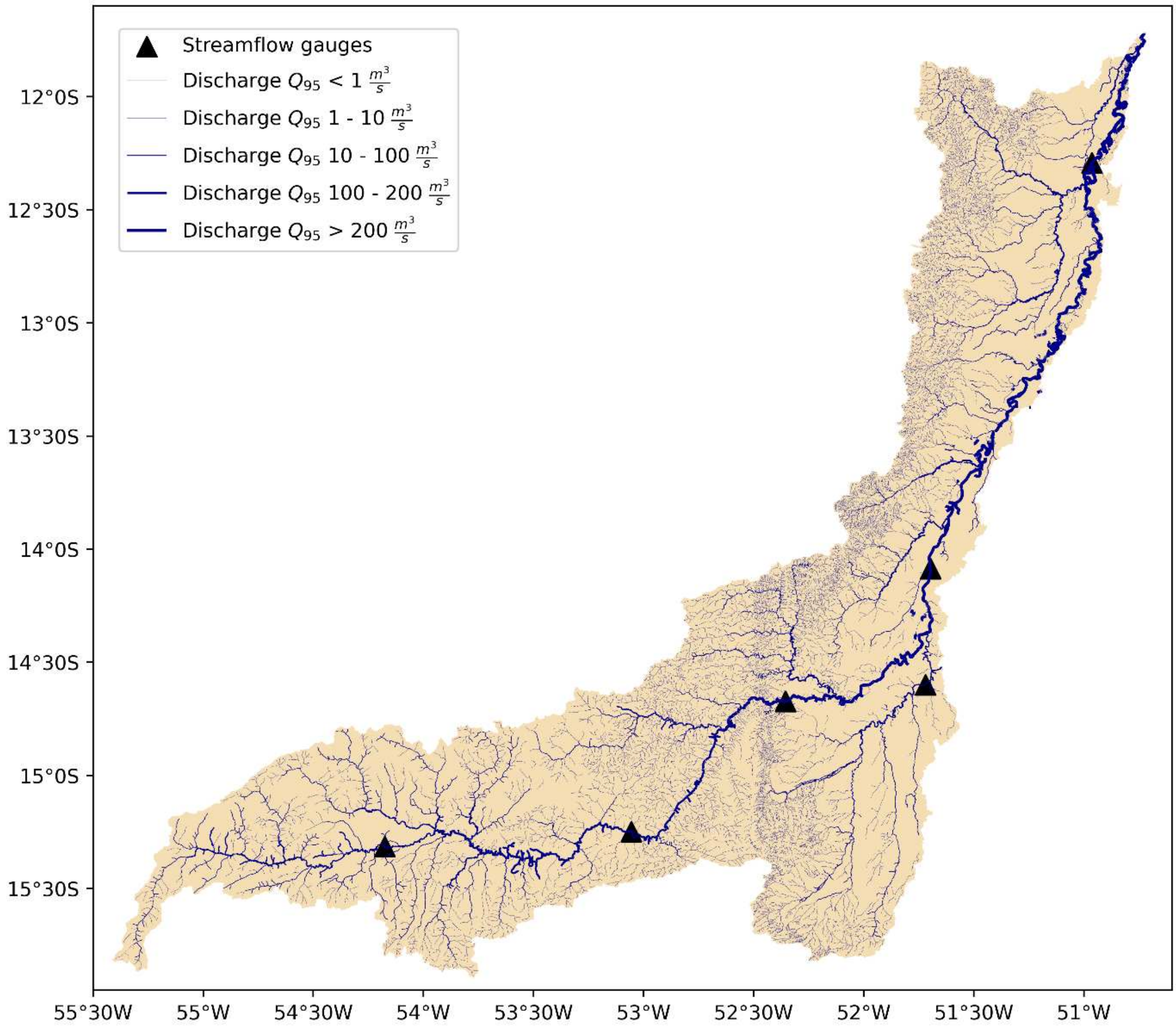

Figure 7. Water availability in Rio das Mortes basin per micro basin after the regionalization. The river's discharge is divided into a logarithmic scale, displayed by different widths of blue lines. The micro basins are category colored by the water used allowed in MT.

Table 6 presents the surface water grants for consumptive uses upstream of the power plants and the maximum discharge intended for consumptive use as specified in the decrees.

Table 6. Water grants upstream of the power plants and the maximum discharge intended for consumptive use as specified in the decrees.

Power plant	Water Grants upstream (m^3/s)	Decree's discharge reservation (m^3/s)
Primavera	6.7	3.5721*
Vila União	6.7	3.5721
Cumbuco	18.6	7.3425
Geóloga Lucimar Gomes	16.1	7.2422
Entre Rios	31.3	-
Salto Belo	0.1	0.2663
Água Limpa	83.1	8.6667

* *Values of Vila União Decree*

The Primavera and Vila União power plants had 6.7 m^3/s of upstream grants and a decree's discharge reservation of 3.5721 m^3/s (Table 6). Although Primavera does not have a specific discharge reservation, it is located very close to Vila União, making it possible to assume the same reservation for both. This proximity also explains why they have the same amount of upstream grants.

The Cumbuco and Geóloga Lucimar Gomes power plants presented similar values of upstream grants, 18.6 m^3/s and 16.1 m^3/s respectively, and decree's discharge reservation, 7.3425 m^3/s and 7.2422 m^3/s, respectively. The Entre Rios power plant granted 31.3 m^3/s of upstream grants; however, the decree's discharge reservation is not specified. Salto Belo had 0.1 m^3/s of upstream grants and a decree's discharge reservation of 0.2663 m^3/s. Água Limpa presented the highest upstream grants of 83.1 m^3/s and a decree's discharge reservation of 8.6667 m^3/s.

3.2.2. RIO DAS MORTES POTENTIAL GROWTH OF IRRIGABLE AREA

The Rio das Mortes subbasin has 1,761,782 ha of suitable areas for irrigation under pasture or agriculture use (Table 5). However, this subbasin also has 2.8 Mha as restricted or wetland areas, 0.3 Mha as suitable areas with native vegetation, and

1.3 Mha classified as unsuitable. Figure 8 shows the suitability classification distribution for the Rio das Mortes subbasin at a spatial resolution of 30 m.

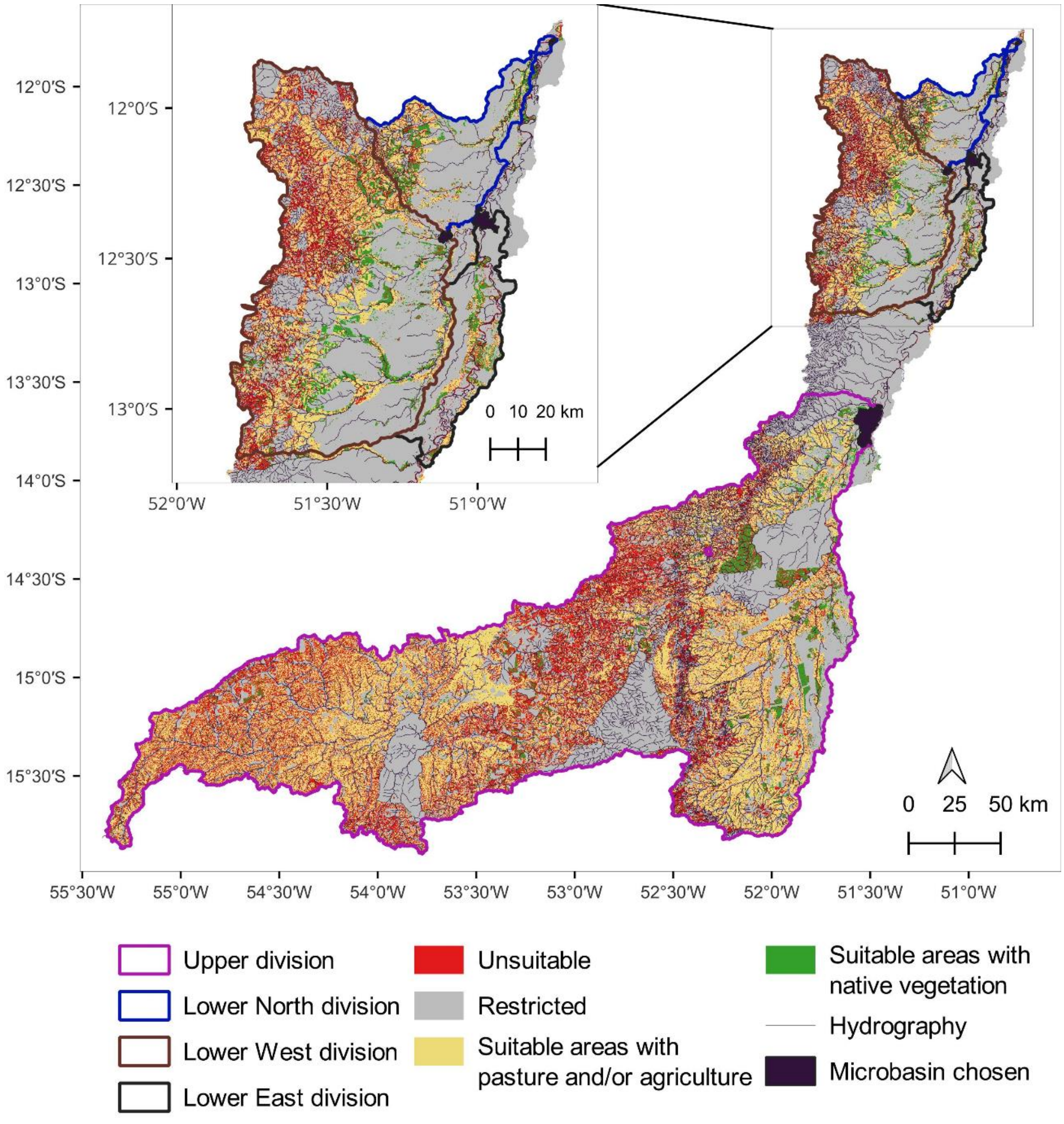

Figure 8. The suitability classification of Rio das Mortes is divided into 4 classes, unsuitable (red), restricted (gray), suitable with native vegetation (green), and suitable with pasture and/or agriculture (yellow). The division of the subbasin into upper (purple), Lower North (blue), Lower West (brown), and Lower West (black) divisions. Hydrography (black lines) and the microbasin chose to the water-limited potential irrigable recalculation (black).

Figure 8 further illustrates how the restricted or wetland lands separate the Rio das Mortes subbasin's suitable areas. Thus, a single, continuous, calculation of water availability is not possible, and the Rio das Mortes basin was subdivided into four continuous areas for calculating the water-limited irrigation expansion potential. Based on the main river's course, the subbasin was divided into Upper, Lower North, Lower West and Lower East divisions, not including large contiguous restricted areas (Figure 8). This division provides more precise values for calculating the water-limited expansion potential.

Accordingly, Table 7 presents the recalculated values for each division, including the regionalized Q_{95}, 70% of Q_{95}, Q_{grants}, $Q_{grantsirrigation}$, and the remaining ungranted flow. The shared and current water-limited irrigation growth potentials were then recalculated based on these revised divisions, using the average $q_{imaxcurrent}$ and average $q_{imaxshared}$ and the maximum potential irrigation growth (ha), which was recalculated because of the limited availability of suitable land.

Table 7. Division area (ha), Q_{95} (m^3/s), 70% Q_{95}(m^3/s), Q_{grants} (m^3/s), $Q_{grantsirrigation}$ (m^3/s), the remaining flow still not granted (m^3/s) and shared and mean with a 95% confidence interval current water limited irrigation growth potential (ha) of each division.

	Upper division	**Lower North division**	**Lower West division**	**Lower East division**	**Total**
Division area (ha)	4,589,626	184,478	783,518	139,994	
Q_{95} (m^3/s)	285.61	17.98	31.85	397.10	
70% Q_{95} (m^3/s)	199.93	12.59	22.30	277.97	
Q_{grants} (m^3/s)	81.04	0.00	0.49	4.34	**85.87**
$Q_{grantsirrigation}$	77.63	0.00	0.48	4.34	**82.45**
70%Q_{95} - Q_{grant}	118.89	12.59	21.81	273.63	
Actual Irrigated Area (ha)	38,616.21	0.00	0.00	0.00	**38,616.21**
Shared water-limited irrigation growth potential (ha)	238,997	25,301	43,834	550,076	**858,210**
Current water-limited irrigation growth potential (ha)	61,917± 13,806 (n=10)	6,554± 1,461 (n=10)	11,356± 2,532 (n=10)	142,508± 31,776 (n=10)	**222,337± 49,575**

Land Suitability for irrigation (ha)	1,527,924	27,482	185,346	12,445	**1,753,197**
Maximum potential irrigation growth (ha)	238,997	25,301	43,834	12,445	**320,127**

In terms of water availability, Table 7 shows that the Upper division (4,589,626 ha) has a Q_{95} discharge of 285.61 m^3/s, significantly lower than the discharge at the mouth of the subbasin (Table 3). The amount of water available for granting (70% of Q_{95}) is 199.93 m^3/s, of which 81.04 m^3/s (40%) has already been allocated in this division. Of these grants, 77.63 m^3/s are designated for irrigation, representing 95% of all grants in the subbasin.

The Lower North division covers 184,478 ha, with a Q_{95} discharge of 17.98 m^3/s, with 70% of Q_{95} of 12.59 m^3/s. This area currently has no allocated water grants. The Lower West division, encompassing 783,518.33 ha, has a Q_{95} discharge of 31.85 m^3/s, with 70% of Q_{95} equating to 22.30 m^3/s. Only 0.5 m^3/s are granted in this division, with 0.48 m^3/s specifically for irrigation purposes. Lastly, the Lower East division, covering 139,994.73 ha, has a Q_{95} discharge of 397.10 m^3/s, of which 277.97 m^3/s could be granted. Currently, all allocated grants in this area, totaling 4.34 m^3/s, are designated for irrigation.

Table 7 also indicates that water grants can safely be expanded within the Rio das Mortes subbasin. Excluding the upper region, which has already allocated 40% of its legal limit, the other divisions have granted less than 2% of their availability, suggesting significant potential for additional allocations. The total water available to be granted in the Rio das Mortes subbasin is 426.91 m^3/s (118.89 m^3/s in the upper division, 12.59 m^3/s in the upper north division, 21.8 m^3/s in the upper west division and 273.63 m^3/s in the upper east division).

Furthermore, Table 7 presents the irrigation growth potential across the Rio das Mortes subbasin divisions under both shared and current water management systems and the land suitability for irrigation. In the Upper division, the potential for irrigation growth under shared management is 238,997 ha, which decreases to 61,917± 13,806 ha under current management. This division has a total area of 4,589,626 ha, with 1,527,924 ha suitable for irrigation.

In the Lower North division, the shared management potential is 25,301 ha, while the current management potential is 6,554 ± 1,461 ha. This division covers 184,478 ha, of which 27,482 ha is suitable for irrigation. The Lower West division has a shared management potential of 43,834 ha and a current management potential of 11,356 ± 2,532 ha. This division has 783,518 ha in total, with 185,346 ha suitable for irrigation. The Lower East division, despite having the highest shared management potential at 550,076 ha and a current management potential of 142,508 ± 31,776 ha, faces significant constraints. This division covers only 139,994 ha, with just 12,445 ha suitable for irrigation.

Overall, the total potential for irrigation expansion across the three divisions is estimated at 858,210 hectares under the shared management system and 222,337 ± 49,575 hectares under the current system. However, the maximum expansion potential in the Rio das Mortes subbasin, analyzed for these scenarios, is limited to 320,127 ha due to the scarcity of suitable land. This result highlights a critical mismatch between the areas with the highest water availability and those with suitable land for irrigation, significantly reducing irrigation expansion.

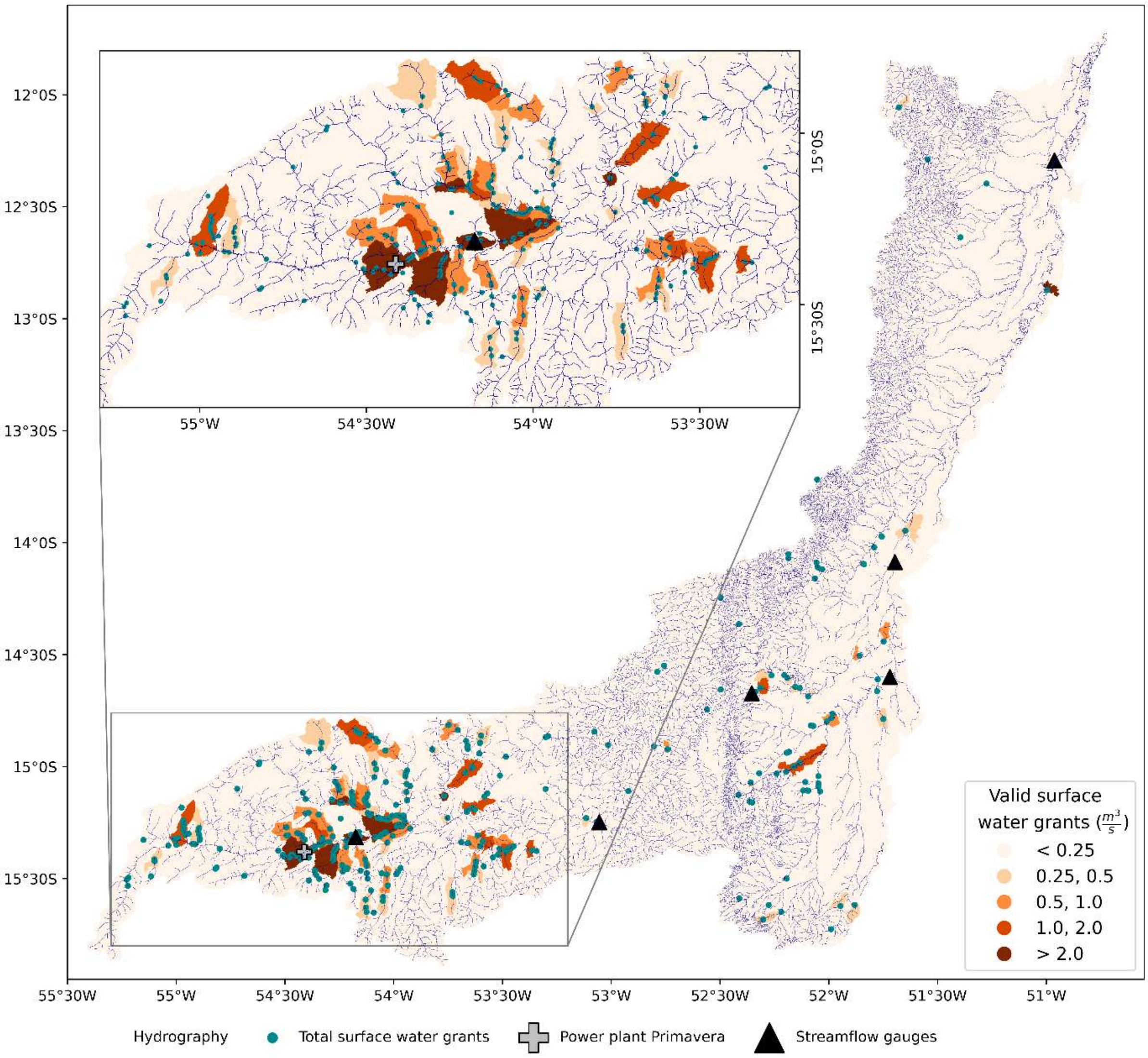

Figure 9. Rio das Mortes subbasin valid surface water grants distribution.

In the water use evaluation, Figure 9 illustrates the distribution of valid surface water in the Rio das Mortes basin. Most valid surface water flows are below 1 m³/s, with higher values concentrated in the Rio das Mortes Irrigation Zone.

Similarly, the distribution of valid surface irrigation water grants shows a high concentration within this irrigation zone, with most grants being under 1 m³/s, as seen in Figure 10.

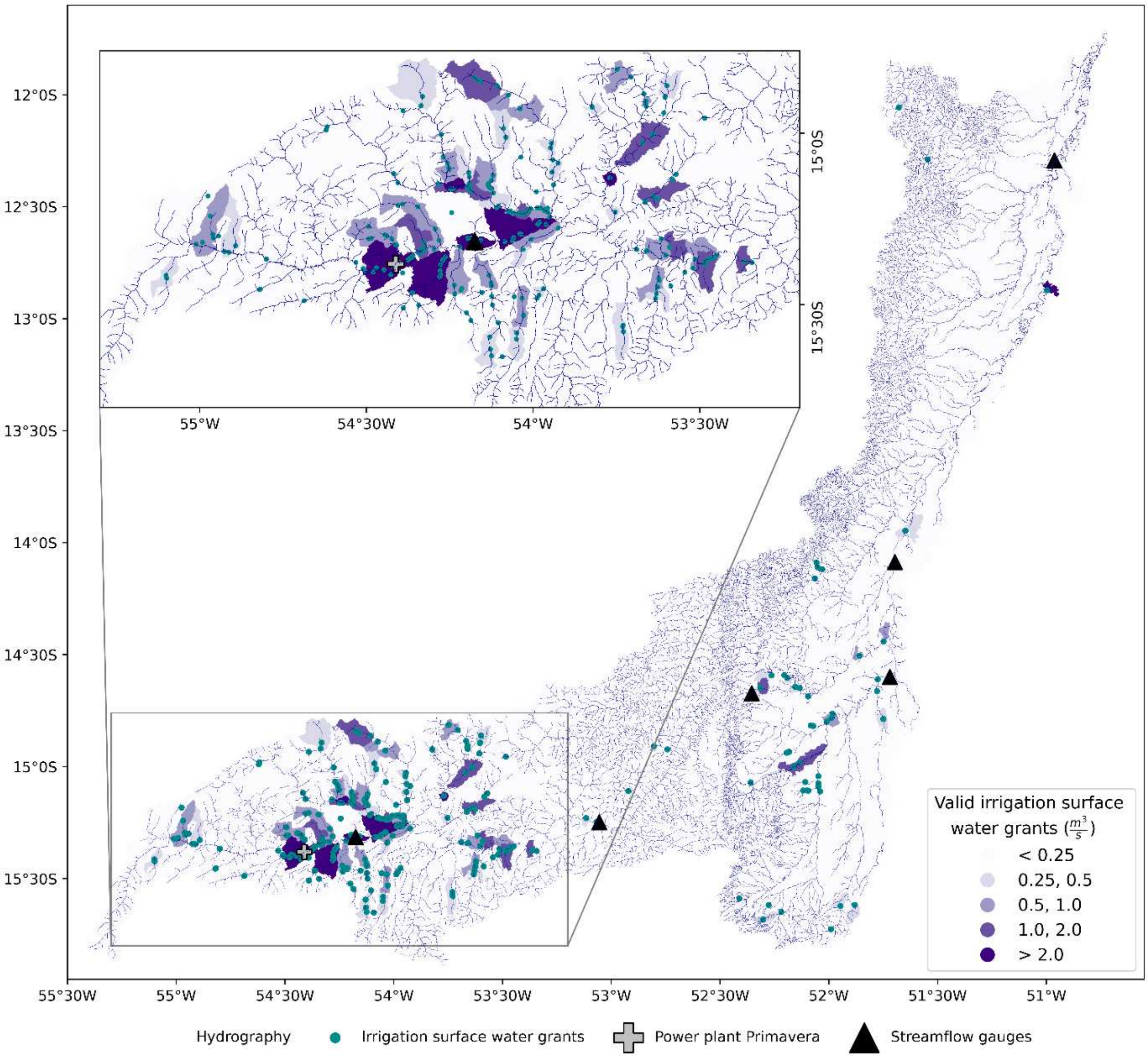

Figure 10. Rio das Mortes subbasin valid irrigation surface water grants distribution.

Figure 11 further reveals that the irrigation pivots are located almost exclusively within the irrigation zone, indicating that irrigation is concentrated in this area.

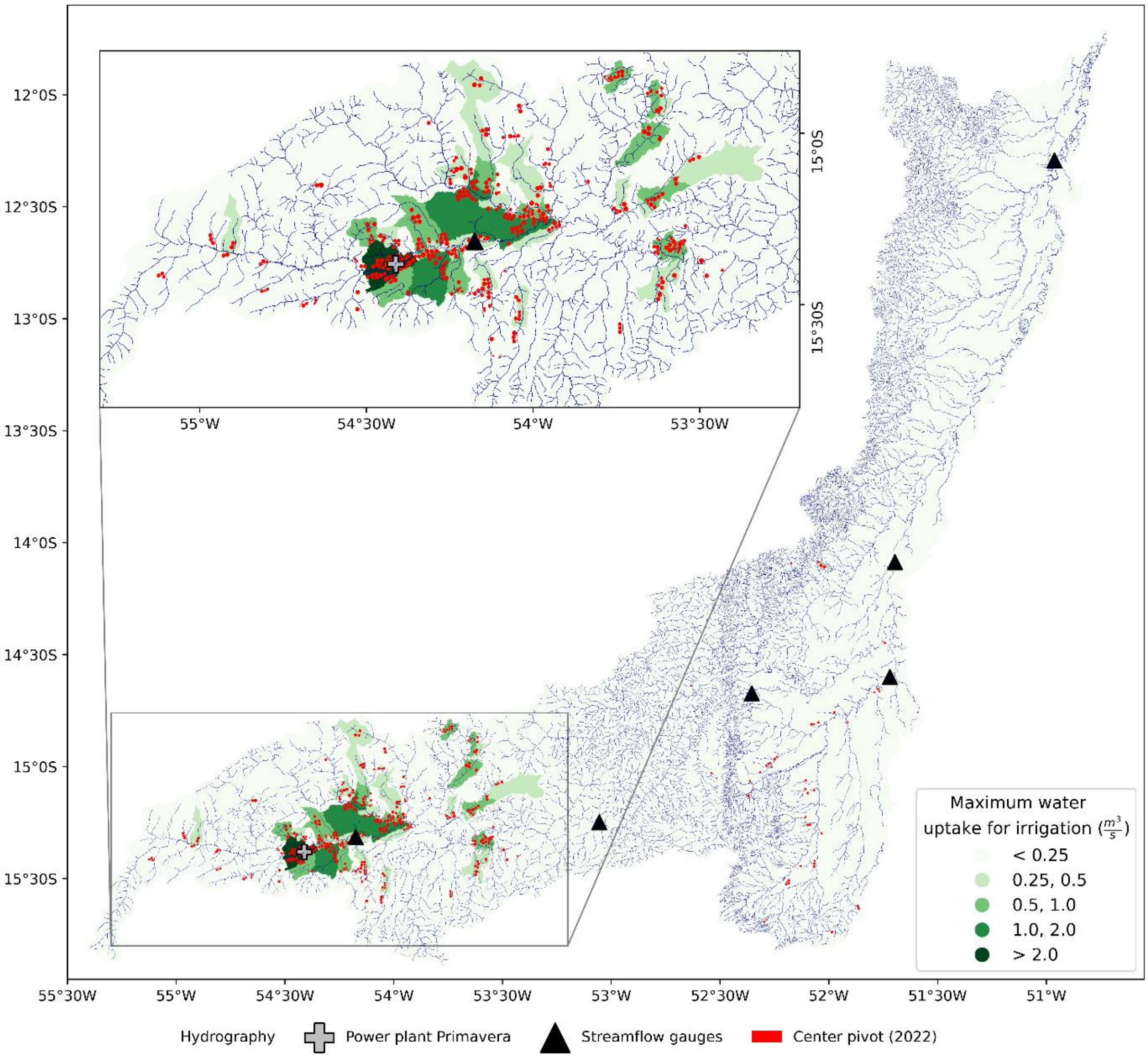

Figure 11. Rio das Mortes subbasin maximum water uptake for irrigation distribution.

The ratio of surface water grants to Q_{95} analysis showed that in the Rio das Mortes basin, a few micro basins have water grants that exceed the state law limit of 70% of Q_{95}, particularly at the river's headwaters. However, the water grants generally do not exceed 50% of Q_{95} in the micro basins of Rio das Mortes. Additionally, in the micro basin where the power plant is located, less than 20% of the Q_{95} is utilized (Figure 12).

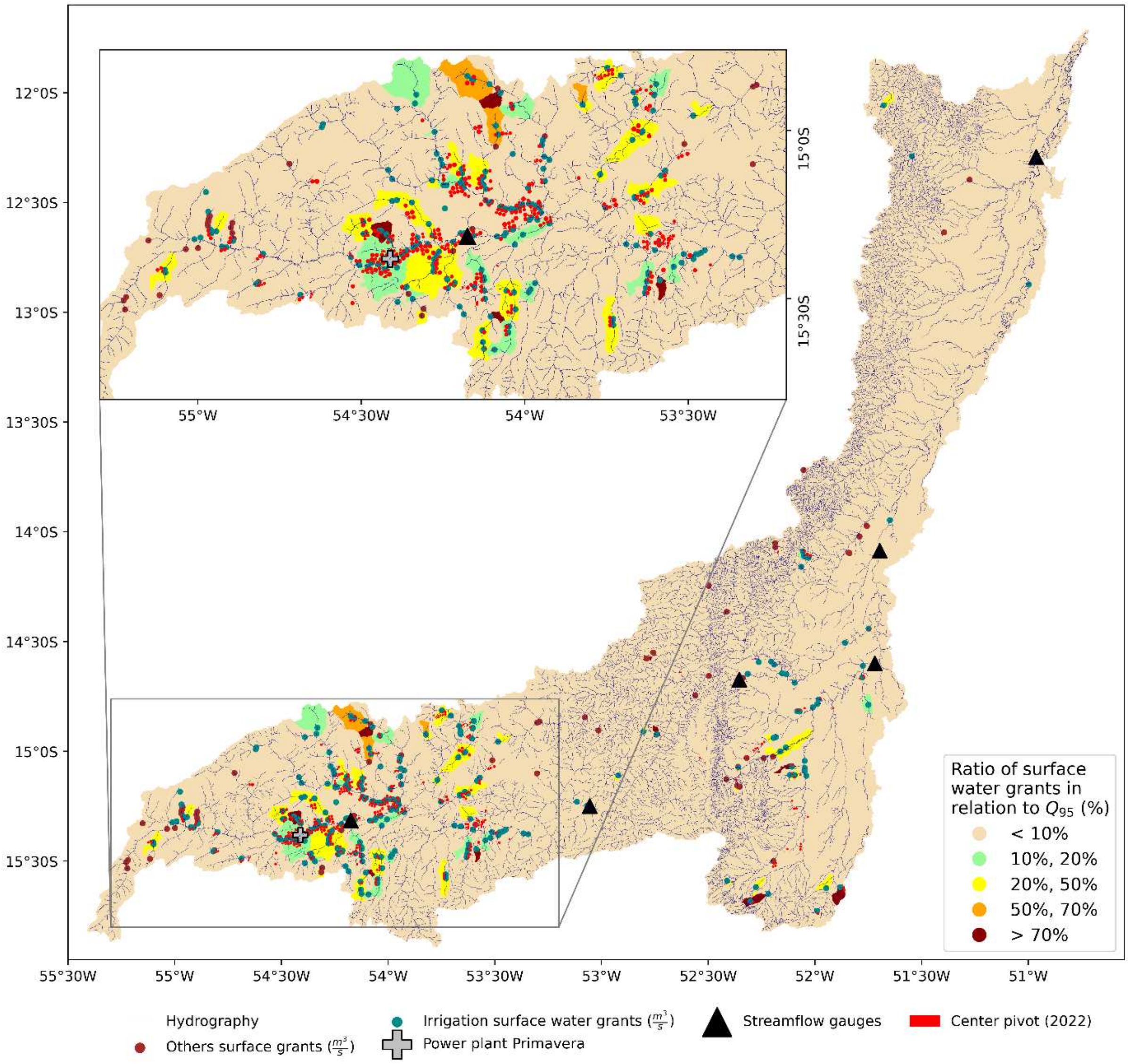

Figure 12. The ratio of surface water granted in the Rio das Mortes basin to water availability per micro basin.

From another perspective, Figure 13 highlights specific micro basins where the calculated water uptake for irrigation surpasses state law limits. In contrast to the patterns observed in Figure 12, Figure 13 shows various micro basins where water usage exceeds 70% of Q_{95}. This can be attributed primarily to pivot crossings at the boundaries of micro basins and the small size of basin divisions, resulting in increased water usage within these micro basins. In other words, due to the small size of the micro basin, the water may be coming from a nearby river in another micro basin.

Overall, these results show that, in general, irrigation is not an issue for water usage in the basin yet, although some individual problems may exist.

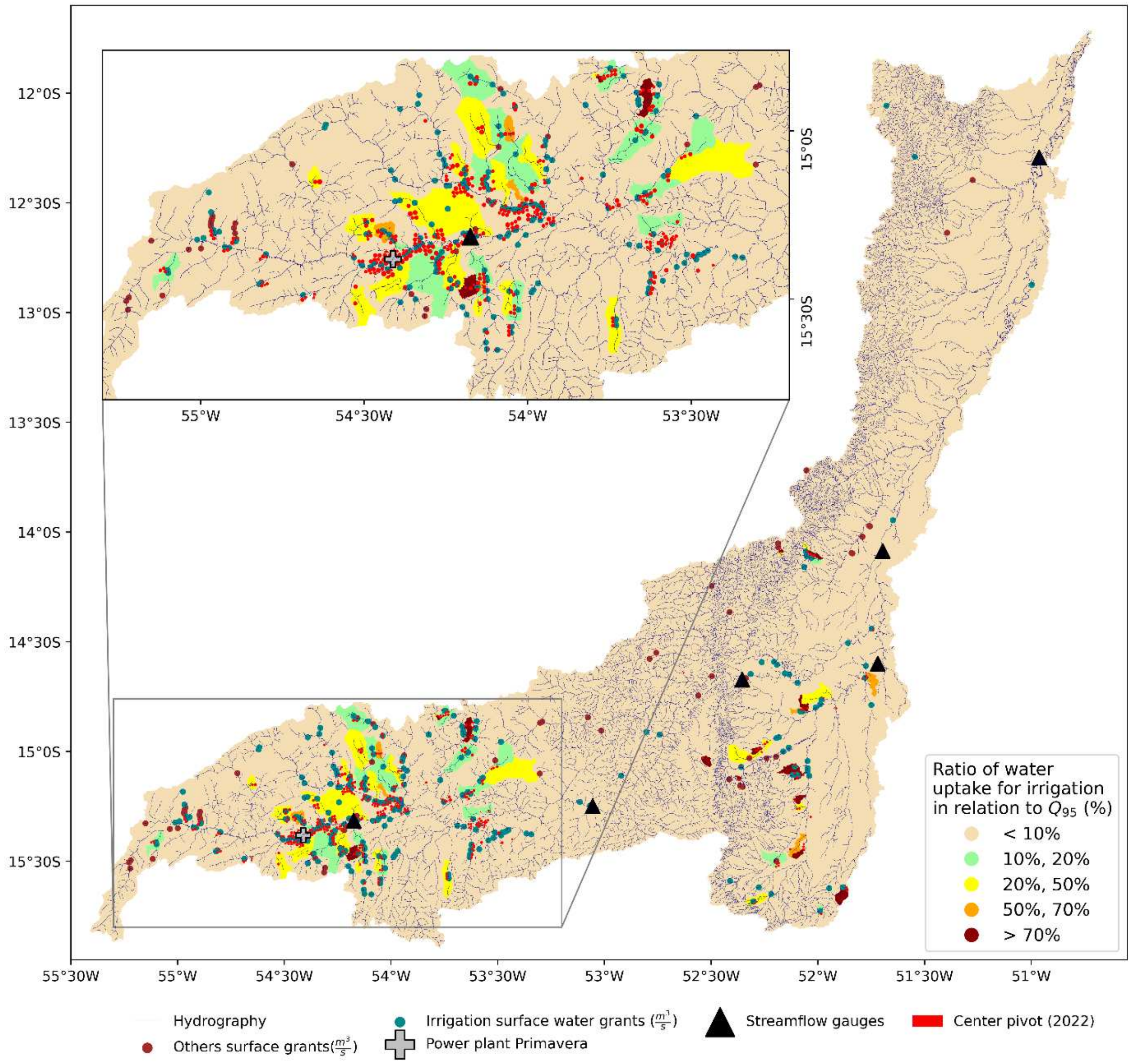

Figure 13. The ratio of water uptake for irrigation in the Rio das Mortes basin to water availability per micro basin.

Figure 14 illustrates the ratio of calculated water uptake for irrigation to surface water grants. Despite the availability of grants, the granted water is not fully utilized, also shown in the results of Table 7. The ratio ranged from 20% to 80%, further supporting the observation from Table 3, which indicates that 87% of Mato Grosso's total surface water grants are designated for irrigation purposes. Despite some irrigation areas operating without state surface grants, there are instances where pivot flows exceed the granted amounts. Figure 13 ensures that these micro basins are not greater than 70% of Q_{95}.

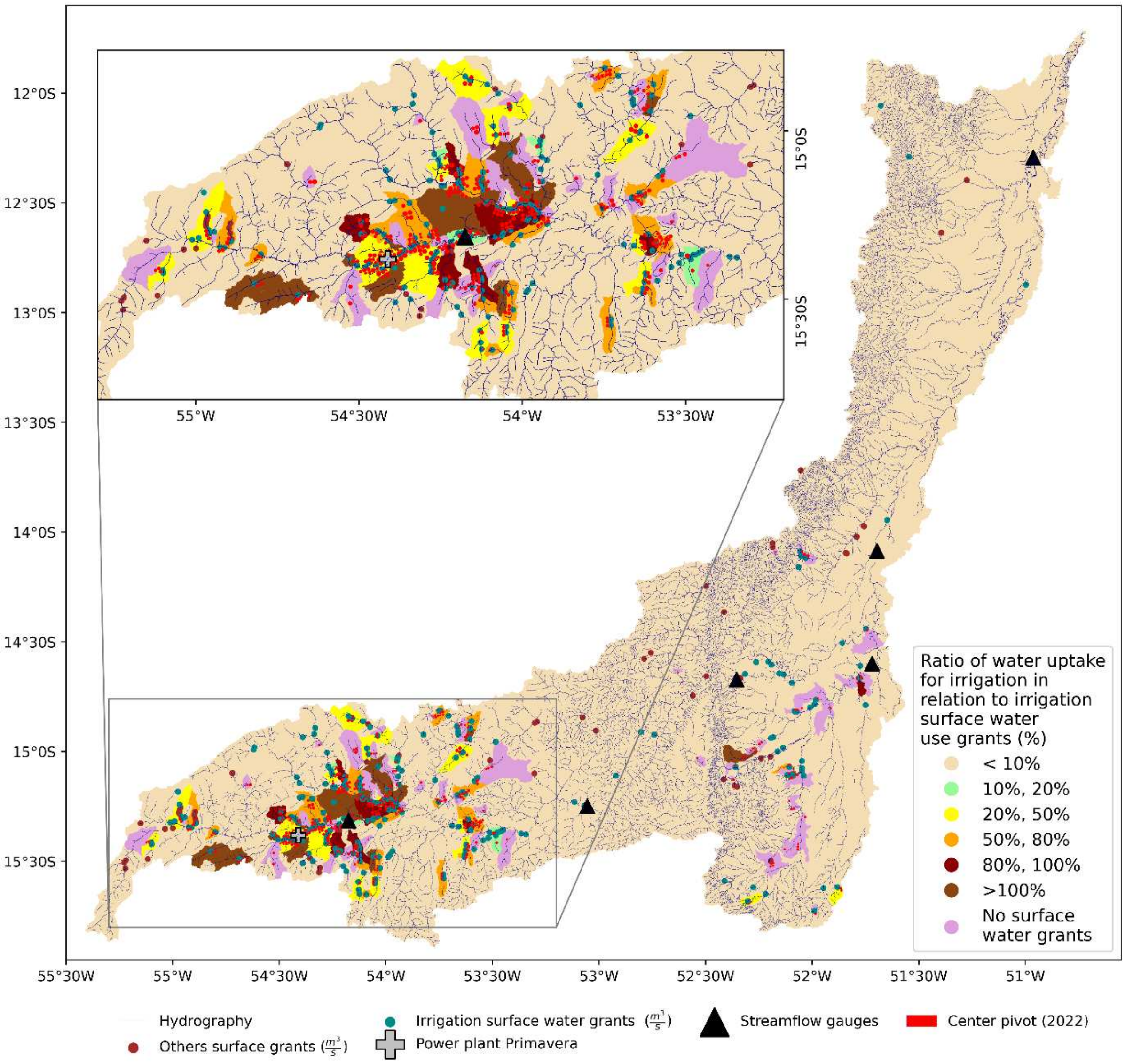

Figure 14. The ratio of water uptake for irrigation in the Rio das Mortes basin to surface water grants per micro basin.

4. DISCUSSION

4.1. Climate variability and agriculture in Mato Grosso

Mato Grosso was the largest grain producer in Brazil in 2024. MT surpassed the state of Paraná in 2000 and continues to be the state with the highest production of soybeans, maize, and cotton in Brazil (IBGE, 2000; IBGE, 2024). The long rainy season and improvements in cropland have driven the rapid expansion of agricultural land in MT (Zhang, et al., 2021). The state has been practicing double cropping since 1990, with soybean-maize and soybean-cotton systems playing a crucial role in the state's economy (Abrahão, et al., 2018). Even though Mato Grosso remains a pillar in grain production in Brazil, Conab, the National Supply Company of Brazil, reports a 15% reduction in 2024 production compared to 2023 (CONAB, 2024). Moreover, the Secretary of Economic Development stated that the regularity of precipitation is the most important factor to ensure yield in MT (Mendes, 2024).

In MT, most of the 21 million hectares of cropland are rainfed, with only 135,000 ha irrigated by center pivots (ANA, 2021). However, climate change poses significant risks to these rainfed systems. Projections indicate a general increase in temperature across the country, with hotter and drier conditions over the continent that threaten crops already nearing their maximum temperature tolerance. Increased temperatures and reduced rainfall are major factors contributing to yield losses in soybean and corn crops (Zhang, et al., 2021; Bigolin, et al., 2024).

Additionally, the rise in global temperatures has increased atmospheric demand for evaporation, which has caused an exponential increase in the vapor pressure deficit in the atmosphere (Yuan, et al., 2019; IPCC, 2021). Elevated vapor pressure deficit increases ET, leading to water stress (Li et al., 2023).

MT's agricultural productivity under rainfed production systems is especially vulnerable to these climate changes. Rising temperatures, an extended dry season, and changes in the spatial and temporal distribution of precipitation driven by global climate change pose additional challenges. Studies indicate that these climatic shifts could substantially reduce the profitability of double-cropping systems in Mato Grosso, largely due to a shortened rainy season (Caruta et al., 2021).

Future climate projections, specifically under the SSP5–8.5 scenario, suggest a decrease in precipitation in the Mato Grosso region (Moon, et al., 2020). This scenario predicts a shorter rainy season, with an expected reduction of up to 5 to 15 days due to a delayed onset in the long term (Commar, et al., 2024).

In the 2023-2024 rainy season, Mato Grosso experienced irregular rainfall patterns and below-average precipitation levels, resulting in a delay of 12 to 30 days in the soybean sowing date for the 2023/2024 crop season, which caused further delays in the maize sowing date and yield losses on maize as a second crop (Santos, 2023; EMBRAPA, 2023). This observed data supports the findings by Brumatti et al. (2020) that postponing the soybean planting operation may not be enough to ensure optimal outcomes for double cropping, especially considering the typical cycle duration of current cultivars.

As high-productivity double cropping requires a rainy season of more than 200 days (Costa, et al., 2019), Mato Grosso's agriculture is susceptible to shortening of the rainy season due to deforestation and climate change (Commar, et al., 2023). Therefore, with the change in precipitation patterns and the high dependence on temperature, climate change brings the biggest challenge to MT: how to increase production without expanding cropland (Dobrovolski, et al., 2015; Franco, et al., 2022).

Studies indicate that agricultural expansion is not a viable solution for yield losses. Researchers have already shown that the conversion of forest to agricultural land affects the hydrological cycle, leading to a progressive decrease in the duration of the rainy season and precipitation, an increase in the frequency of drought periods, generalized regional warming, and a reduction in evapotranspiration in the state's predominant biomes, the Amazon and Cerrado (Leite-Filho, et al., 2019; Leite-Filho, et al., 2020; Leite-Filho, et al., 2021; Wongchuig, et al., 2022). Because of land cover-climate feedback, expansion over the Amazon rainforest region can result in reduced productivity and negative economic consequences linked to agricultural activities. Studies also reveal that regions with extensive cultivation and diminished natural land cover experience substantial local yield deficits (Commar, et al., 2023; Lark, et al., 2020). Furthermore, the conservation of biomes is crucial for maintaining highly productive agriculture, emphasizing the need for sustainable land use practices (Brumatti, et al., 2020).

For this to be achievable, the new model for developing food production in tropical agriculture should be highly intensive, involving two or more crop cycles per year with high productivity, environmental protection, economic sustainability in production, improved quality of life for rural communities, and strict control over resource use such as water and energy (Franco, et al., 2022). In this context, intensification is proposed to increase food production without expanding into new areas for cultivation, thereby minimizing pressure on native vegetation. This approach reduces the conversion of these areas into croplands by employing improved production methods, including fertilizers, double cropping, and irrigation (Viera, et al., 2022).

As global warming and population growth become more pressing, increasing concerns about water and food security, irrigation becomes essential in adapting to future food crises and the effects of climate change. Irrigation is the most efficient method to address water scarcity in agriculture, significantly supporting global food security. It accounts for 40% of global food production using only 22% of the world's cultivated land (Qin, et al., 2024). Unplanned expansion of irrigation, however, may compromise water security.

4.2. Planning for sustainable expansion of irrigation in Mato Grosso

ANA (2021) estimated an expansion of the irrigable area of 9.8 million hectares using only surface water resources in MT, while this study estimates between 2 Mha and 6 Mha, depending on the water granting system used.

Both the ANA study and this study share similar methodologies: focus on areas currently used for agriculture and pasture, rely on surface water sources only, calculate flow rates using Q_{95} values from fluviometric gauges and from modeled regionalized Q_{95} discharge (as in the Rio das Mortes case study), and exclude already granted discharges. However, the studies diverge in their approaches to water demand by crop. While ANA uses reference crop water requirements, this study evaluates actual irrigation practices analogous to a shared water management system that considers peak water uptake and current management policies for valid irrigation grants.

The shared system is based on the joint use of water resources by multiple users within a single system, advocating for the shared management of water resources among users. On the other hand, the current water granting system is essentially individualistic, where water usage rights are granted to specific users, and each user has individual rights over their granted water (ANA, 2009).

Expanding on ANA's approach, this study introduces a new perspective by assessing the total area available for irrigation expansion based solely on land suitability. Additionally, it provides a refined estimate of expansion potential, divided by the main rivers in the state, while incorporating uncertainty analysis to evaluate the reliability and quality of the data used.

By examining how farmers manage water use under shared and current policy and considering Mato Grosso's high water availability (Table 3) under stationary discharge patterns, the findings indicate that agriculture could intensify on nearly 6 million hectares, constrained by water availability under the shared management system and almost 2 million hectares under the current management system. This is within the broader potential of 17 million hectares of land deemed suitable for agriculture and/or pasture (Table 5). Under the current system, water reserved for the farmers per ha for irrigation is approximately four times higher than in the shared system. This higher water reservation directly impacts the available area for irrigation expansion across all the subbasins studied (Table 5). Other Brazilian states such as Minas Gerais and Goiás, have already taken legislative steps toward incorporating the new concept of multiple users sharing water resources (GOAIS, 2024; ALMG, 2024).

Specifically, Rio Madeirinha, Rio Roosevelt, Rio Guariba, and Rio Aripuanã, located in the Amazon biome, contain large areas designated as conservation units and indigenous lands, with low pasture areas (as shown in Figures 1 and 2). Despite having considerable suitable land and water availability for potential irrigation expansion (Tables 3 and 5), the subbasins are in the Amazon biome, making expansion in these areas not recommended. Figure 6 illustrates that these four subbasins have several areas with restrictions and unsuitable conditions for expansion.

Although protected areas largely dominate the Rio Juruena landscape, large contiguous areas are available for irrigation expansion (Figure 1 and Figure 6). Therefore, the full potential for expanding irrigated areas in Rio Juruena can be realized by occupying 73% of the already cleared land for agriculture and pasture based on the shared system and 19% based on the current system (Table 5). Rio Juruena also presents many hydropower plants in the territory, mostly in the southwest of the subbasin (Figure 1).

The Rio Teles Pires subbasin has had an official Irrigation Zone in its southern part since 2023 (MIDR, 2023), indicating a well-established irrigated agriculture. Figures 6 and Table 5 indicate that Rio Teles Pires has extensive land suitable for irrigation expansion. The full potential for irrigated area expansion in shared management can be realized with only 34% of the suitable area being utilized, leaving 66% still available. In the current scenario, the expansion of irrigation can be done using only 9% of the available suitable land.

Moreover, although the Rio Xingu subbasin has over 3.6 million ha of land suitable for irrigation expansion, the presence of indigenous territory along the main course of the Rio Xingu limits the full utilization of the river's water potential. However, the water-limited irrigation growth potential in both scenarios, as shown in Table 5, can still be fully achieved in areas surrounding the conservation unit, ensuring that expansion respects the protected regions.

Continuing, the Rio Guaporé subbasin, characterized by its extensive pasture areas (Figure 1), however, sustainable growth based on available water resources can be realized in only 11% of this area under a shared water management system. Under the current management system, this percentage is even lower, using just 3% of the suitable land (Table 5). This means its water availability can be fully utilized without causing additional deforestation.

For the Rio Paraguai subbasin, despite the high flow of water allowed by law calculated, only 3% of this amount is currently used for irrigation purposes (Tables 3 and 5). The underdeveloped state of irrigation and the abundance of suitable lands leave this subbasin with the third highest potential for irrigation expansion based on water availability, second only to the Rio Juruena and Rio Araguaia subbasins, without the need to expand the cropland frontier (Table 5).

Lastly, the Rio Araguaia subbasin, despite having many restricted areas in the north, has a significant potential for irrigation expansion due to its already extensive agricultural activities, particularly in the Rio das Mortes Irrigation Zone (Figure 1 and Figure 5). This makes it possible to expand irrigation without converting new areas. Intensification can occur in at least 40% of the suitable land based on the shared system and less than 11% in the current system.

Based on water availability (Table 5), the potential growth in irrigated areas in MT could result in a 4,700% increase in the shared system and 1,400% in the current system compared to the current irrigation area. This growth would be sustainable, based on water consumption that does not exceed the locally renewable water available on the surface.

Studies indicate that production per unit of area can increase 3.7 times through intensification combined with mechanization and modernization of agricultural systems (Qin, et al., 2024). Double cropping and intensification would help prevent larger local yield deficits, as seen in areas worldwide where greater cultivation occurs alongside the preservation of natural land, preventing croplands from moving to lower-quality and less suitable regions (Lark, et al., 2020). Implementing sustainable irrigation on water-stressed rainfed croplands is a significant adaptation and mitigation measure. It can provide a reliable water supply to water-stressed crops, alleviate heat stress, and contribute to more reliable and resilient crop production (Rosa, 2022).

Overall, Mato Grosso has many suitable areas with existing agriculture and pastures with sufficient water resources for expansion, allowing agricultural intensification through irrigation without converting new areas into cropland. Nevertheless, as indicated in Table 5, the potential for expansion is significantly lower under the current water management system than a shared management system. This difference raises a discussion about improving water resource management policies at the state level for irrigation.

Studies indicate that shared system management is a valuable approach for strengthening the regulatory capacity of the state, mitigating the effects of water scarcity, preventing conflicts over water use in critical sections, improving water resource management, facilitating access for users who need this model, and promoting the rational use of water resources, as already seen in other states in Brazil (Silva, 2024; Fonseca, 2023; Marques, et al., 2021). These outcomes in other Brazilian states align with the findings in Table 5, which would make Mato Grosso reach its full irrigation expansion potential.

Moreover, Mato Grosso faces significant challenges in optimizing irrigation to support agricultural intensification due to monitoring infrastructure and data quality limitations, which affect water availability and expansion assessments. The major challenge is the limited monitoring network across the state. The World Meteorological Organization (WMO) standards recommend one fluviometric station per 1000 km^2 of land area, which would imply > 900 operational stations in the state. Currently, only 41% of Mato Grosso's 156 stations (64 stations) meet essential criteria for area coverage and data availability. The operational station density is 0.07 stations per km^2, 7% of the minimum recommended by WMO, highlighting the need for a more robust, comprehensive monitoring network. For approximately half of the subbasins analyzed, including Rio Madeirinha, Rio Roosevelt, Rio Guariba, Rio Aripuanã, Rio Iriri, and Rio Xingu, only one monitoring station meets both the discharge area and 80% data coverage criteria.

In subbasins such as Rio Juruena and Rio Guaporé, these limited data sources lead to substantial estimation uncertainties. For Rio Juruena, the confidence interval is 35% of the mean discharge, and in Rio Guaporé it is 69%, which calls into question the reliability of water availability estimates for water use purposes. Table 3 highlights that, in the case of Rio Guaporé, the confidence interval exceeds the mean remaining flow still not granted, jeopardizing the assessment of water resources availability.

For subbasins with multiple stations, Rio Teles Pires with seven stations, and Rio Paraguai with eleven, the variance in Q_{95} estimates is reduced to 18% and 15%, respectively, underscoring how improved data availability enhances estimation accuracy. However, the Rio Araguaia subbasin, despite having nine stations, still demonstrates significant uncertainty (52% of the mean), indicating the need for further improvements in monitoring.

Comparisons between the Q_{95} estimates from this study (Table 3) and those from ANA (2021), where the first values in parentheses reflect ANA's calculations, show close alignment for Rio Madeirinha (23.77 m^3/s vs 25.65 m^3/s, 7.9% difference) and Rio Juruena (2,020.46 m^3/s vs 2,209.68 ± 784.87, 9.4% mean difference). However, for other subbasins, including Rio Roosevelt (175.88 m^3/s vs 107.80 m^3/s 38.7% difference), Rio Guariba (17.45 m^3/s vs 26.36 $^3/s$, 51.1% difference), Rio Aripuanã (73.87 m^3/s vs 96.81 m^3/s, 32.4% difference), Rio Teles Pires (629.30 m^3/s, vs 781.41 ± 143.18, 24.2% mean difference), Rio Iriri (2.37 m^3/s vs 15.51 m^3/s, 554.4% difference), Rio Xingu (818.53 m^3/s vs 424.63, 48.1% difference), Rio Guaporé (75.04 m^3/s vs 103.65 ± 72.21 m^3/s, 38.1% mean difference), Rio Paraguai (801.66 m^3/s vs 992.71 ± 145.07 m^3/s, 23,8% mean difference), Rio Araguaia (761.01 m^3/s vs 1055.84 ± 317.90 m^3/s, 38,7% mean difference), and Rio das Mortes (322.21 m^3/s vs 417.64 m^3/s, 29.6% difference), there are notable discrepancies, underscoring the need for enhanced monitoring management.

Furthermore, the uncertainties highlighted in water availability significantly impact estimates for expanding irrigation areas. In the shared water management system, the peak water uptake for irrigation lacks a confidence interval, highlighting the need to account for uncertainties in water availability. Rio Guaporé has considerable uncertainty since the confidence interval exceeds the mean irrigation area expansion potential. In the Rio Araguaia subbasin, the confidence interval represents roughly 52% of the mean, similar to the Rio Juruena subbasin, where the confidence interval constitutes about 56% of the mean.

Nonetheless, Table 5 suggests that expansion managed under the current water granting system exhibits fewer uncertainties, attributed to more stable and localized water granting practices, with an average variance of 20% in several subbasins, including Rio Madeirinha, Rio Roosevelt, Rio Guariba, Rio Aripuanã, Rio Iriri, Rio Xingu, and Rio das Mortes, which previously lacked confidence intervals. The Rio Juruena subbasin also shows a 20% uncertainty, while the Rio Guaporé subbasin continues to exhibit a high variance of 29%. The Rio Teles Pires, Rio Paraguai, and Rio Araguaia subbasins show a reduced variance of around 10%. These lower uncertainties suggest that the subdivision of the Rio das Mortes subbasin, as shown in Figure 3 and Table 4, may play a critical role in obtaining more reliable estimates for irrigation expansion. Therefore, expanding and improving the monitoring network is essential for achieving reliable and accurate estimates in Mato Grosso.

4.3. The Rio das Mortes case study

In this case study, Rio das Mortes demonstrates a considerable potential for agricultural intensification through irrigation without requiring additional land conversion. A total of 1,753,197.85 ha of land is suitable for expanding irrigation, but this potential is not uniformly distributed across the subbasin's divisions (Figure 8) and the maximum expansion potential (Table 7), is constrained to 320,127 ha because of the limited availability of suitable land.

The Upper division, which contains the established Irrigation Zone (Figure 1), concentrates most of the suitable land. Despite this, water availability limits the potential for expansion to 16% of the suitable land under the shared management system and 4% under the current system (Table 7). This allows for significant increases in irrigated areas, an expansion of 619% in the shared management scenario (from 38,616 ha to 238,997 ha) and 160% in the current system (from 38,616 ha to 61,917 ha), without additional deforestation (Table 4 and 7).

In the Lower East division, the irrigation growth potential is considerably high, representing 64% of the total potential for expansion (550,076 ha out of 858,210 ha). However, this division faces limitations in terms of available land, meaning that the potential expansion for irrigation exceeds not only the suitable area but also the Lower East division's total area. This imbalance emphasizes that even where water availability is sufficient, land characteristics may limit practical irrigation expansion. In the Lower West division, although a large area is present, the amount of suitable land is reduced due to the presence of wetlands, which restricts irrigation expansion (Figure

8 and Table 7). Finally, excluding the Lower divisions, Rio das Mortes can achieve its full irrigation potential within suitable land areas without further deforestation.

Nevertheless, a more detailed examination of water usage in the Rio das Mortes subbasin reveals a less optimistic scenario. Water usage is granted only after SEMA analyzes water availability through the Hydrological Regionalization Study of Mato Grosso and evaluates existing demands within the subbasin (SEMA, 2024). However, an analysis of water stress by micro basin indicates that, in some areas, the water usage grants exceed the Q_{95} limits (Figures 12 and 13). This finding suggests that over-granting problems may be happening in the headwaters. As a caveat, the reported over-granting is calculated using this regionalized discharge dataset. SEMA may be using a different regionalization product, which may explain the few over-granting cases. Although SEMA employs continuous monitoring equipment for measurements and generates annual reports on monthly discharge withdrawals (SEMA, 2024) internal administrative issues related to the transition from a physical to a digital system have posed challenges (Rodrigo, 2024). These issues can lead to difficulties in properly managing water resources, thereby impacting the sustainable expansion of irrigation.

Additionally, an informal conversation with farmers and center pivot sales representatives indicated that a typical irrigation water grant in the Rio das Mortes subbasin is around 1 L s^{-1} ha^{-1}. This rate sheds light on a new perspective for interpreting irrigation expansion estimation, not only in this subbasin but throughout the entire state. The use of 1 L s^{-1} ha^{-1} as a standard rate suggests that farmers may irrigate less land than their water grants could technically support, which aligns with observations in Figure 14. Moreover, the peak collective use of water resources in the area is 0.497 L s^{-1} ha^{-1}, which confirms that farmers, on average, use much less water than they are granted, and reinforces the importance of the choice of the criterion of allocating water resources on the potential for expansion.

Furthermore, the Rio das Mortes subbasin also presents another issue regarding water usage, specifically the Declaration of Reservation of Hydrological Availability (DRDH). Currently, Rio das Mortes has only one operational power plant but plans for six more under construction. The reservation is granted based on average monthly flows, subtracting reserved flows for upstream consumptive uses and remaining flows in the Total Available Volume (10% of average monthly flows). However, Mato Grosso has already granted more water usage rights than the decree reserves, excluding the Salto Belo power plant (Table 6).

For instance, the Água Limpa power plant’s reservation grant is only 10% of the discharge already granted, explained by the DRDH being requested in 2010 before significant growth in grants for irrigation purposes (Table 3). Despite this, the DRDH for newer power plants like Geóloga Lucimar Gomes and Vila União in 2022 still does not reflect the current realities of the subbasin. This misalignment could hinder the sustainable expansion of irrigation.

Additionally, indigenous populations in the Rio das Mortes basin have reported violations in the licensing process for hydropower projects. These projects include the Entre Rios, Vila União, Cumbuco, and Geóloga Lucimar Gomes power plants, which are located at the headwaters of the Rio das Mortes and the Cumbuco River. These rivers flow through several Indigenous territories, such as Sangradouro/Volta Grande, Merure, São Marcos, Areões, Pimentel Barbosa, and Wedezé (Midia Jur, 2024).

Furthermore, several hydropower projects are being planned for the Rio das Mortes basin, even though Mato Grosso already has 82 operational power plants with a total installed capacity of 3,000 MW (Ager, 2024).

Finally, these issues related to multiple water uses could jeopardize the expansion in the Rio das Mortes subbasin. To ensure sustainable expansion, even though all subbasins have suitable lands and water resources for intensification, detailed work evaluating multiple uses of water is necessary across all subbasins in Mato Grosso. This will ensure that all subbasins have a favorable expansion scenario and sustainable water usage.

5. CONCLUSIONS

In conclusion, this study supports irrigation as a viable strategy for agricultural adaptation in Mato Grosso, enabling increased productivity, reduced yield deficits, and more resilient crop production in a climate change scenario. The analysis highlights the potential to expand irrigation across two water management scenarios without surpassing local renewable water resources. Under a shared water management approach, 6,376,076 ± 1,727,727 hectares of suitable land could be irrigated, while 1,912,478 ± 303,381 hectares could be added under the current water granting system. In both cases, all expansion can be done in areas previously cleared, without additional deforestation.

However, Mato Grosso faces significant data limitations, particularly regarding discharge information for its subbasins, leading to uncertainties about the true potential for irrigation expansion. While previous ANA calculations estimated a 9.8 million ha expansion, this study presents a more conservative estimate, though uncertainties remain. Improving the hydroclimatic observation network in the basin is crucial to reducing these uncertainties.

To fully achieve the expansion potential identified here, the adoption of a shared water management system is recommended. Also, the state must address multiple water use needs across all subbasins, ensuring that suitable lands and water resources are managed effectively to support agricultural intensification.

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APPENDIX A

A1. HYDROPOWER PLANT PRIMAVERA

Hydorpower plant Primavera began operations on November 30, 1995. With an installed capacity of 11.80 MW, Primavera received its water use grant through a Decree from Brazil's Casa Civil in December 1997, valid until December 11, 2027. However, the amount of water reserved for this power plant is not specified in the decree.

A2. HYDROPOWER PLANT CUMBUCO

The Cumbuco power plant, situated along the Rio Cumbuco, a tributary of the Rio das Mortes, operates under the regulations outlined in Decree No. 985 of 18 November 2022 from Mato Grosso's Secretariat of Environment. This decree reserves the affluent natural flow for the Cumbuco power plant, although the hydrological series is not published in the decree.

The decree includes details about water usage, such as flows allocated for consumptive uses upstream in the Rio Cumbuco basin, as indicated in Table A1. Additionally, Table A2 specifies the minimum remaining flows required to be maintained in the TVR - Reduced Flow Section, ensuring environmental sustainability. The validity of the decree extends until November 30, 2024, with the possibility of renewal for an additional three years.

Table A1. Flows intended for consumptive uses in the Rio Cumbuco basin upstream of the Cumbuco power plant.

Year	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**	**2057**
Discharge (m^3/s)	5.2353	5.8897	6.2824	6.4132	6.7012	7.0676	7.1985	7.3425

Table A2. Minimum Remaining Flows to be maintained in the TVR – Reduced Flow Section.

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Discharge (m^3/s)	9.61	10.21	10.33	8.73	6.58	5.42	4.74	4.30	4.28	4.67	5.87	7.92

A3. HYDROPOWER PLANT SALTO BELO

The Salto Belo power plant, located along the Rio Noidore, a tributary of the Rio das Mortes, operates under the regulations outlined in Decree No. 133 of February 28, 2022, emitted by Mato Grosso's Secretariat of Environment. This decree reserves the natural flow upstream of water for the Salto Belo power plant, as shown in Table A3.

Table A3. Monthly minimum, mean, and maximum discharges of Rio Noidore upstream of the Salto Belo power plant from 1965 to 2007 as published in the decree.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum Discharge (m^3/s)	7.38	7.32	8.42	6.54	6.31	5.55	5.44	5.15	5.32	6.77	6.94	7.59
Mean Discharge (m^3/s)	13.28	13.67	13.54	11.43	10.09	9.18	8.41	8.11	8.51	9.45	10.63	12.27
Maximum Discharge (m^3/s)	17.08	21.93	19.40	15.71	14.15	15.80	11.73	1.20	12.84	12.28	18.14	16.43

The decree also provides details about water usage, including the flows allocated for consumptive uses upstream of the Salto Belo power plant, as indicated in Table A4. Additionally, Table A5 specifies the minimum remaining flows that must be maintained in the TVR - Reduced Flow Section. The decree was valid until June 26, 2022.

Table A4. Flows intended for consumptive uses upstream of the Salto Belo power plant.

Year	2020	2025
Discharge (m^3/s)	0.2131	0.2663

Table 8. Minimum Remaining Flows to be maintained in the TVR – Reduced Flow Section.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Discharge (m^3/s)	1.328	1.367	1.143	1.009	0.918	0.918	0.841	0.811	0.851	0.945	1.063	1.227

A4. HYDROPOWER PLANT ÁGUA LIMPA

The Água Limpa power plant operates under the regulations outlined in Decree No. 119 of July 15, 2010, issued by Mato Grosso's Secretariat of Environment. Located along the main course of the Rio das Mortes, this decree reserves the natural flow of water upstream for the Água Limpa power plant, as shown in Table A6.

Table A6. Monthly minimum, mean, and maximum discharges of Rio das Mortes River upstream of the Água Limpa power plant from 1931 to 2007 as published in the decree.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum Discharge (m³/s)	206	200	257	178	169	14	132	124	101	118	137	113
Mean Discharge (m³/s)	462	509	546	415	312	258	227	198	192	217	263	360
Maximum Discharge (m³/s)	960	935	1148	763	551	395	342	288	280	353	450	789

The decree also provides details about water usage, including the flows allocated for consumptive uses upstream of the Água Limpa power plant, as indicated in Table A7. Additionally, Table A8 specifies the minimum remaining flows that must be maintained upstream of the Água Limpa power plant. The decree was valid until June 26, 2022.

Table A7. Flows intended for consumptive uses upstream of the Água Limpa power plant.

Year	2015	2020	2025	2030	2035	2040	2045
Discharge (m³/s)	7.6154	7.7906	7.9658	8.1411	8.3163	8.4915	8.6667

Table A8. The remaining Flows are to be maintained upstream of the Água Limpa power plant.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Discharge (m³/s)	46.2	50.9	54.6	41.5	31.2	25.8	22.7	19.8	19.2	21.7	26.2	26.0

A5. HYDROPOWER PLANT GEÓLOGA LUCIMAR GOMES

The Geóloga Lucimar Gomes power plant, located along the Rio Cumbuco, a tributary of the Rio das Mortes, operates under the regulations outlined in Decree No. 720 of September 1, 2022, emitted by Mato Grosso's Secretariat of Environment. This decree reserves the natural flow upstream of water for the Geóloga Lucimar Gomes power plant, as shown in Table A9.

Table A9. Monthly minimum, mean, and maximum discharges of Rio Cumbuco upstream of the Salto Belo power plant from 1968 to 2014 as published in the decree.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum Discharge (m³/s)	39.35	45.04	52.75	42.53	34.16	29.47	26.12	24.45	23.44	27.13	34.66	33.99
Mean Discharge (m³/s)	87.61	93.40	94.58	79.03	58.08	46.85	40.22	35.93	35.68	39.52	51.18	71.16
Maximum Discharge (m³/s)	163.3	164.4	134.8	114.9	87.41	73.85	58.84	57.33	52.98	56.07	78.53	108.2

The decree also provides details about water usage, including the flows allocated for consumptive uses upstream of the Geóloga Lucimar Gomes power plant, as indicated in Table A10. Additionally, Table A11 specifies the minimum remaining flows that must be maintained in the TVR - Reduced Flow Section. The decree is valid until August 31, 2025.

Table A10. Flows intended for consumptive uses upstream of the Salto Belo power plant.

Year	2022	2027	2032	2037	2042	2047	2052	2057
Discharge (m³/s)	5.1709	5.8173	6.2051	6.3343	6.6187	6.9807	7.1100	7.2522

Table A11. Minimum Remaining Flows to be maintained in the TVR – Reduced Flow Section.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Discharge (m³/s)	11.664	12.242	12.360	10.805	8.710	7.587	6.924	6.496	6.471	6.854	8.021	10.018

A6. HIDROPOWER PLANT VILA UNIÃO

The Vila União power plant operates under the regulations outlined in Decree No. 898 of October 20, 2022, emitted by Mato Grosso's Secretariat of Environment. Located along the main course of the Rio das Mortes, this decree reserves the natural flow of water upstream for the Vila União power plant, as shown in Table A12.

Table A12. Monthly minimum, mean, and maximum discharges of Rio das Mortes River upstream of the Vila União power plant from 1976 to 2014 as published in the decree.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum Discharge (m³/s)	81.5	76.9	86.1	65.9	71.4	63.8	58.4	55.3	53.8	57.8	68.6	70.8
Mean Discharge (m³/s)	113.0	118.8	130.6	115.6	91.4	79.2	70.7	65.3	65.3	69.1	79.4	97.3
Maximum Discharge (m³/s)	174.4	179.0	197.3	159.2	124.9	96.0	90.0	88.2	83.3	89.9	100.5	147.7

The decree also provides details about water usage, including the flows allocated for consumptive uses upstream of the Vila União power plant, as indicated in Table A13. Additionally, Table A14 specifies the minimum remaining flows that must be maintained upstream of the Água Limpa power plant. The decree is valid until October 30, 2025.

Table A13. Flows intended for consumptive uses upstream of the Vila União power plant.

Year	2022	2027	2032	2037	2042	2047	2052	2057
Discharge (m³/s)	3.3489	3.3808	3.4127	3.4446	3.4765	3.5084	3.5402	3.5721

Table A14. The remaining Flows will be maintained upstream of the Água Limpa power plant.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Discharge (m³/s)	13.17	13.75	14.93	13.43	11.01	9.79	8.94	8.40	8.40	8.78	9.81	11.60

APPENDIX B

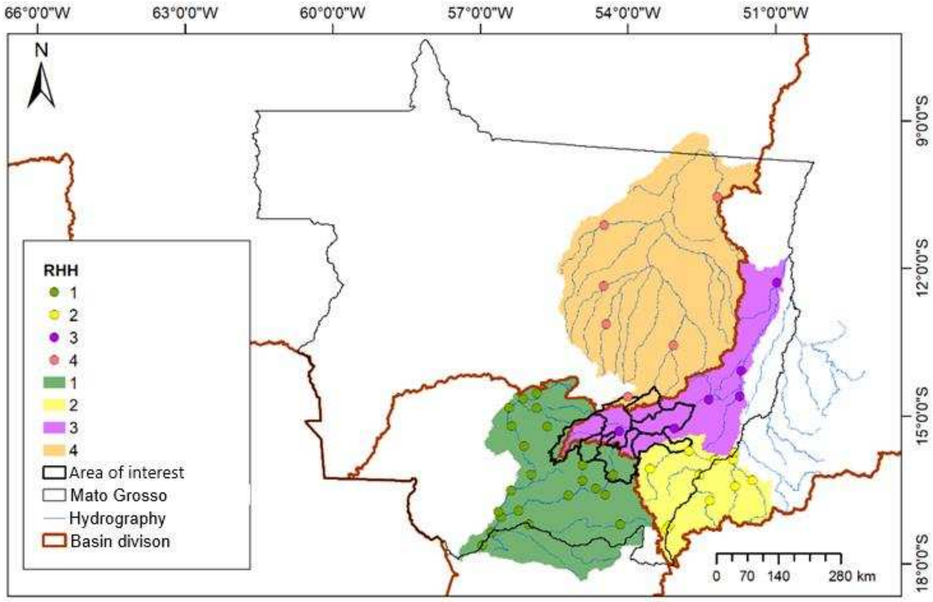

Figure B1. Homogeneous Hydrological Regions (RHH) used in the regionalization study.

Table B1. Adjusted regionalization equations for Q_{95}.

RHH	Equation	r^2
1	$Q_{95} = 0{,}176293\ Peq^{0{,}922594}$	0,87
2	$Q_{95} = 0{,}042329\ Peq^{1{,}114067}$	0,81
3	$Q_{95} = 2{,}479354\ E\text{-}47\ A^{0{,}984408}\ P^{14{,}014856}$	0,98
4	$Q_{95} = 4{,}30931178\ E\text{-}10 A^{0{,}752689}\ P^{2{,}516346}$	0,95

Table B2. Regionalization equations with imposition for Q_{95}.

RHH	Equation
1	$Q_{95} = 0{,}01264\ A$
2	$Q_{95} = 0{,}0185277\ A$
3	$Q_{95} = 0{,}013523\ A$
4	$Q_{95} = 0{,}0100355\ A$

Where Peq is a two-dimensional variable that represents the flow equivalent to the volume precipitated in a given drainage area, P is the precipitation, mm and A is drainage area, km^2.

APPENDIX C

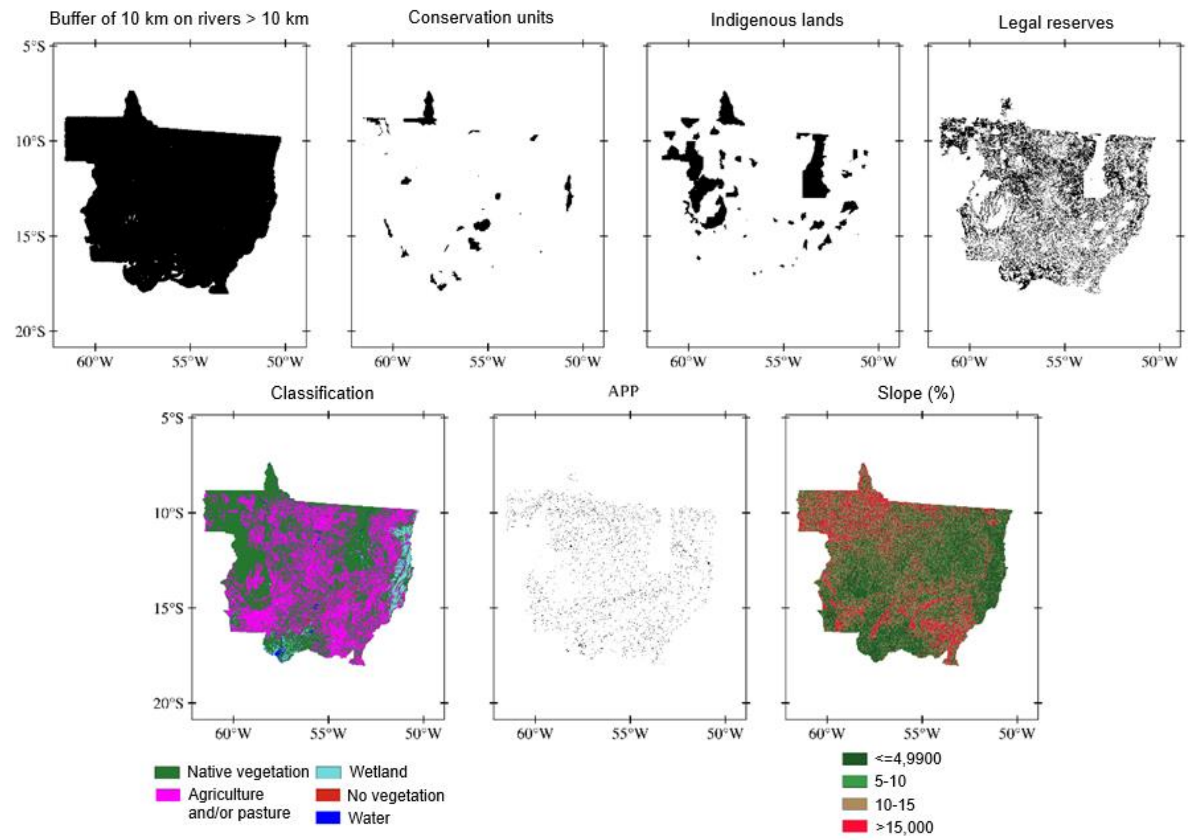

Figure C1. Data used for the selection of areas suitable for irrigation expansion.