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Analyzing the impact of agricultural water-demand management on water availability in the Urubu River basin – Tocantins, Brazil

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ABSTRACT

The Urubu River is part of the Formoso River Basin located in Tocantins State in northern Brazil. It is an important agricultural region where irrigation has an important role in rice and soybean crops, cultivated during the rainy and the dry seasons, respectively. The high levels of irrigation associated with below-average precipitation in 2016 and in the following years resulted in a water crisis in the Urubu Basin, with serious consequences to the environment and the economy of the region. This work evaluated the impact of reducing irrigation on environmental flows in the Urubu River Basin using hydrological modeling in WEAP. Irrigation water demand scenarios were simulated and analyzed from July 2018 through June 2019. Results indicated the need to reduce 35% of all water withdrawls in order to avoid the interruption of flow in the Urubu River Basin. This percentage was even greater when only some of the farmers cooperated. The paper emphasized that it is important that all farmers be involved and cooperate to reduce their water withdrawal by any means, including improving their irrigation system efficiency. The water regulator may also motivate water withdrawal reduction by modifying water permits and applying water withdrawal restrictions during the dry season.

Keywords: hydrological modeling, scenario analysis, water balance.

Análise da influência da gestão de demanda agrícola na disponibilidade hídrica da bacia hidrográfica do Rio Urubu – Tocantins, Brasil

RESUMO

O rio Urubu faz parte da bacia hidrográfica do rio Formoso, localizado no estado do Tocantins na região Norte do Brasil, sendo uma importante região agrícola e com forte utilização da irrigação para fortalecer a produção de arroz, cultivado na estação chuvosa, e em especial da soja para semente, durante a estação seca. A elevada dependência da irrigação associada a uma pluviosidade abaixo da média registrada no ano de 2016 que se estendeu pelos anos seguintes, ocasionou um período de escassez hídrica com impactos ambientais severos na bacia do rio Urubu. A disponibilidade hídrica na Bacia foi modelada com uso da ferramenta WEAP, com o objetivo de avaliar a necessidade de alteração das demandas de água para irrigação, buscando manter uma mínima vazão remanescente no rio Urubu. Para isso foram simulados cenários de redução percentual da vazão captada pelas bombas hidráulicas de irrigação. O período de análise foi de julho 2018 a junho de 2019 devido à restrição de disponibilidade de dados. Os resultados dos cenários indicam a necessidade de redução de 35% da demanda de referência para evitar uma interrupção na vazão do rio, sendo esse valor ainda maior na quando uma parcela dos agricultores não reduza o consumo. Para mudança da gestão dos recursos hídricos na bacia do rio Urubu, a participação dos diversos agentes se mostra fundamental, onde é preciso aumentar a eficiência na irrigação aliando alterações nos limites de outorgas de uso da água e aplicação de restrições de captação na estação seca.

Palavras-chave: análise de cenários, balanço hidrológico, modelo hidrológico.

1. INTRODUCTION

The planning and management of water resources aim to ensure access to water in adequate quantity and quality for a variety of water users while alleviating possible conflicts among them. The management structure focuses not only on meeting the water demand related to human activities, such as drinking water, sanitation and hygiene, industries, and irrigation but also on defining alternatives that allow the protection of environmental quality, including the groundwater and its ecology (Tundisi, 2013). According to Bernardi *et al.* (2012) the management of the water resources on the geographic limits of the watershed makes it possible to evaluate the singularities associated with each of the sub-basins, taking into account the stakeholders (social and economic aspects) and the physical and climatic characteristics, together with the available alternatives of policies and solutions.

Understanding the water balance of a river basin thus proves to be an important first step for the water-resource planning and management and can assist in the decision-making process, strengthening environmental protection and water security in the river basin. Considering that the greatest water user in Brazil is the irrigation sector, approaching almost 50% of the total water demand (ANA, 2020), many studies have focused on advancing the knowledge of water balance in different river basins and enhancing the water-resource management in these areas (Mendes *et al.*, 2021; Albuquerque *et al.*, 2019; Abreu and Tonello, 2018). Many efforts have also been developed to incorporate water demand management as an important step to reduce water shortage and improve production in agricultural river basins. Water demand management in the agriculture sector focuses on changes in crop and irrigation techniques, intensification of data monitoring and optimization of irrigation methods (Almeida *et al.*, 2021; Beltrão Júnior, 2017; Nikoo *et al.*, 2022; Srinivasan *et al.*, 2022).

The State of Tocantins (TO) has a flat landscape, fertile soils in excellent condition, a tropical climate, good water availability and suitable road infrastructures. All of these are important advantages for agricultural production, allowing the development of agriculture and livestock as the most significant economic sectors in the state (Tocantins, 2016). Tocantins State is a highlight in the Brazilian scenario as an agricultural power in expansion with an arable area that corresponds to half of the total area of the state, reaching 13.8 million hectares. In 2021, according to the Ministry of Agriculture, Livestock, and Supply (Brasil, 2021), the State reached the mark of US$3.36 billion in Gross Value of Agricultural Production (GVP), consolidating itself as the third state in the Northern Region and in the eleventh state in Brazil, summing a total of US$ 202.2 billion in GVP amounts converted on 12/31/2021 according to

Banco Central do Brasil registration. According to the Systematic Survey of Agricultural Production, the 2021 highlights in agricultural production in the Tocantins were soybeans (9.8 million tons), corn (1.5 million tons), and rice (1.2 million tons), which reached the third position in the country's production ranking, following the states of Rio Grande do Sul (13.6 million tons) and Santa Catarina (1.9 million tons) (IBGE, 2022; Brasil, 2022).

The Formoso River Basin is in the area of the PRODOESTE state program that encourages the development of irrigated agriculture. Its flat and naturally flooded topography favors the production of rice on its floodplains during the rainy season. During the dry season (May through November), other crops are cultivated, such as beans, watermelon and especially soybean seeds (Tocantins, 2016; Santos and Rabelo, 2008; Faria *et al.*, 2018; Vergara *et al.*, 2013).

Irrigation is especially important during the dry season, between May and November, resulting in the issuance of 99% of water grants to irrigators (Vergara *et al.*, 2013; Magalhães Filho *et al.*, 2015). The agricultural water withdrawal in the Formoso River is carried out by 98 hydraulic pumps with an average capacity of 1,620 L s-1, adding up to 158,100 L s-1 if they are all turned on at the same time. These pumps are located along the main rivers in the region, the Formoso, the Urubu, the Dueré, and the Xavante, but most of them are installed near the mouth of the Formoso (IAC, 2017; 2018; Faria *et al.*, 2018).

In 2016, the Formoso River Basin faced a water crisis due to a drought event combined with antropic actions (Fleischmann *et al.*, 2017). However, a set of components were considered the drivers of the high risk of the environmental impact registered in the region, such as high level of water demand for irrigation, lack of water levels monitoring, lack of supervision and application of water policies aimed to preserve the availability of water resources (NATURATINS, 2016; IAC, 2018).

With the purpose of informing the management of water resources and preventing water shortage, an increase in the application of socio hydrological models capable of simulating the impact of human decisions in the hydrological processes has been observed all over the world. These modeling tools can help the management of water resources, increasing the understanding of hydrological, economic, and social dynamics at a watershed scale (Magalhães and Barp, 2014). In addition, these models allow the evaluation of alternative scenarios, simulating the performance of policies and management measures through these scenarios. This process has been proved to favor the implementation of effective policies and management actions building flexibility, robustness and resilience to the system. (McPhail *et al.*, 2018; Ermolieva *et al*., 2022; Narita *et al*., 2022).

The “scenario discovery” methodology has emerged as an alternative to the traditional approach of “predict and act” analysis. The process consists of building a set of scenarios showing slight variations from a baseline or reference scenario, similar to a sensitivity analysis. In many cases, this reference scenario represents the current situation in a watershed. For the other scenarios, variations of some specific group of parameters or characteristics are built in a set of other scenarios and the performance of the policies is tested under this new set of scenarios (Silva *et al*, 2017; Mhiribidi *et al.*, 2018; Gorgoglione *et al.*; 2019).

The *Water Evaluation and Planning System* (WEAP) developed by the Stockholm Environmental Institute and later improved by the *Hydrologic Engineering Center* (HEC) of the US Army Corps of Engineers (USACE - US Army Corps of Engineers), is a computational tool capable of modeling hydrological systems. WEAP is based on mass balance principles applied to a net of nodes and links, which represents the water-resource system to be modeled. Some of these elements of the system are reservoirs, rivers, water demand points, water and sewage treatment plants and urban centers (SEI, 2016).

WEAP allows the comparison of water availability and the demand required between the reference scenario and any alternative scenarios in a simplified and visually accessible way. It shows graphs and tables that facilitate the decision-making process. Alternative scenarios can incorporate the most variable scenario changes, such as increased efficiency in the pumping system, evaluation of water management actions and policies, changing crop selection and production practices, population increase and other characteristics of the water system. (SEI, 2016).

The WEAP model has been applied in many studies to evaluate the reliability of irrigation systems in regions that intend to expand the agricultural area, to evaluate best management practices and their impact on the irrigation system efficiency, to assess the impact on water supply due to increase in wastewater discharge from industries and to analyze public policies and development plans. In addition, the WEAP model has been widely applied to assess future scenarios of climate change and its possible consequences on water balance, agricultural productivity and the future need to expand water supply to meet drought events (Gao *et al.*, 2017; Mirdashtvan *et al*., 2021; Layani and Bakhshoodeh, 2021; Asitatikie and Gebeyehu, 2021; Noon *et al*., 2022).

The hydrological and human system combined in the Formoso River Basin requires efforts to improve knowledge concerning the dynamics of interaction among social, hydrological and economic systems in the region. The Formoso River simulation model may give insights on water policies that could enhance the reliability of the irrigation system together with the protection of environmental flows in the basin that is an important area of grain production in the country, with a great impact on the regional economy (Magalhães Filho *et al.*, 2015, IAC, 2018).

In this sense, the objective of this study was to carry out a scenario-based analysis to assess water balance in the Urubu River, given the need to reduce the demand for water for irrigation as a way of preserving the local ecosystem. The study is a pioneering analysis of the hydrological system in the Urubu/TO River Basin. The basin encompasses extensive agricultural areas of rice and soybean for seeds crops with many water pumps that in 2016 motivated the interruption of the river flow during a drought that hit the region.

The work is an effort of research that has being developed in the Formoso River Basin and uses monitoring data from the High-Level Management (GAN) research project, a pioneer in Brazil to use technology to register real-time data of flows and water withdrawals for irrigation, contributing to more efficient management and inspection actions (IAC, 2018). The study evaluated alternatives to water demand management to avoid future water crises and conflicts in the Urubu River Basin, and illustrates how demand management arrangements and high technology applied to data monitoring can increase the efficiency of irrigation systems and water use in agriculture, avoiding water shortage. The analysis illustrated the importance of cooperation among farmers, favoring possible collective benefits in the river basin while at the same time protecting environmental flows and general conditions.

2. METHODOLOGY

The selected study area is the Urubu River Basin, which represents 29% of the total area of the Formoso River Basin covering a total of 6,183 km² in the State of Tocantins (TO) in the northern region of the country, as presented in Figure 1. The Dueré River Basin covers 3,553 km² converges to the mouth of the Urubu Basin, influencing the availability of water in the last two water pumps installed in the Urubu River.

The basin is located in the Cerrado biome, presenting a dry and humid tropical climate and a defined rainy season between December and April, and a dry season between May and November. The precipitation regime presents great variability between the dry and the rainy seasons. Although the annual average of precipitation is considered high, around 1579.6 mm, the average precipitation during the most critical months, from June to August, is only 6 mm

(Valente *et al.*, 2013; Alvez *et al.*, 2014; 2016).

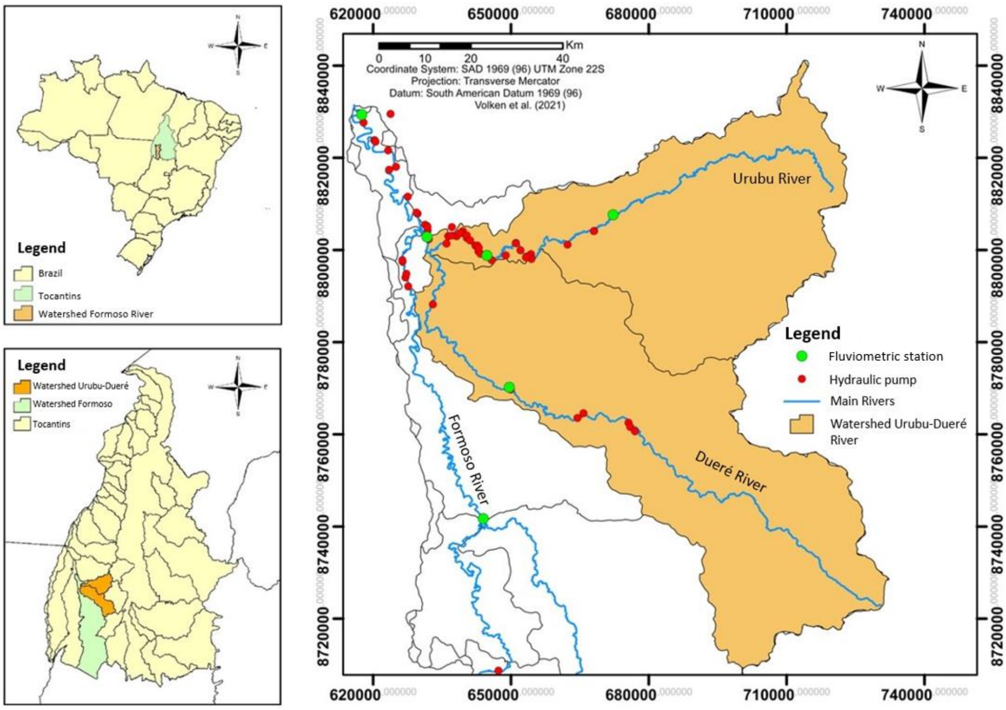

Figure 1. Location of the Urubu and Dueré River Basins (tributaries), in the State of Tocantins.

Although there are three discharge stations in the Urubu River Basin, Foz Rio Urubu (26798500), Fazenda Fortaleza (26795700), and Fazenda São Bento (26795100), and one in the Dueré River Basin, Foz Rio Dueré (26792000), the historical series of flow data start in 2017 and have many missing values, resulting in low confidence in the records. Thus, the methodology applied in this work and presented in Figure 2 sought to propose a framework to contribute to the understanding of the water balance in the study area. The flows in the Urubu and Dueré Rivers were simulated to build the reference scenario, where the water demands for agriculture were evaluated in order to define water resource allocation scenarios.

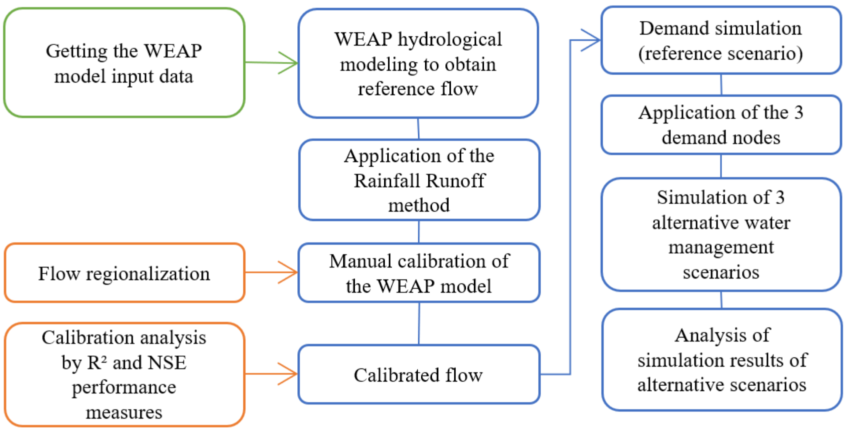

Figure 2. Methodological flowchart applied in the study of water balance analysis in the Urubu and Dueré River Basins.

Reference flow and water balance in the Urubu River Basin, including the Dueré Sub-basin, was modeled using the *Water Evaluation And Planning System* (WEAP), as illustrated in Figure 3. The simulation period encompassed July 2018 to June 2019, given the best availability of data in a daily time step. The Urubu River Basin and the Dueré River Basin were represented in the WEAP model by two basin nodes. Three nodes, D1, D2 and D3 represented the set of water demand sites along the Urubu River.

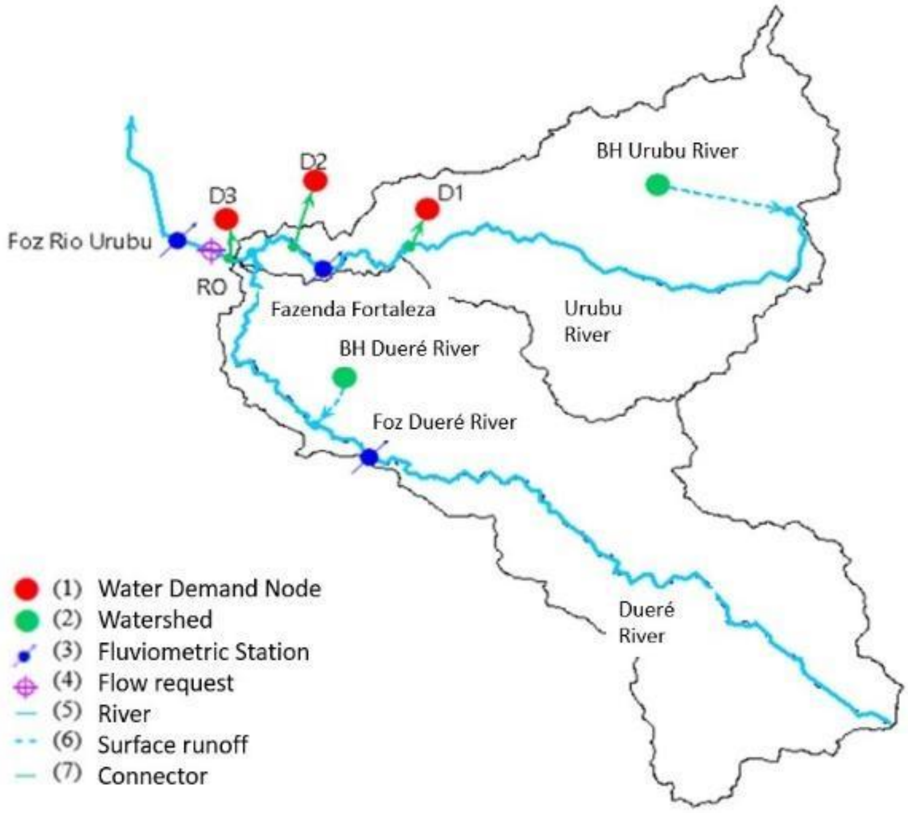

Figure 3. Water resource network in WEAP representation. (Urubu and Dueré River Basins – Tocantins).

The streamflow in the node representing the Urubu River was simulated using the Rainfall Runoff (Soil Moisture Method) Module in the WEAP. The method considers two one-dimensional layers of soil, surface and deep. The following processes are simulated in the upper soil layer (surface): evapotranspiration, surface runoff, soil moisture and percolation into the lower soil layer. The base flow, the deep soil moisture changes and the water flow into the aquifers are simulated in the deep soil layer module. The input data for the Rainfall Runoff method are climate data, soil type and land-use data, spatially distributed in the sub-basins defined by the users. This method is considered the most complete in all hydrologic models in WEAP (SEI, 2016).

The streamflow simulation was performed using the *Rainfall-Runoff (Soil blend Method*) module considering the parameters and configuration presented in Table 1 and Figure 4. The climate data used in this research is presented in Table 2. The average daily rainfall over the areas of the Urubu and Dueré River Basins was the result of the application of the Thiessen method using the rainfall stations in Table 3.

The streamflow modeling calibration was based on graph comparisons using three streamflow gauges in the basin, the Urubu River outlet (code 26798500), the Fortaleza Farm (code 26798500) and the Praia Alta (code 26720000. All three streamflow gages are in the Formoso River Basin. Initially, the author analyzed the environmental characteristics of the basin, such as area, perimeter, main channel length, drainage density, compactness coefficient, circulatory ratio and factor form in order to perform the regionalization of flows among these gauges using the linear interpolation method.

Table 1. Input data in the method Rainfall-Runoff in the WEAP model to obtain the streamflow of the Urubu and Dueré Rivers. *WEAP (suggested system data) **GIS (Geographic Information System).

Land use	Category	Value	Unit	Source	Resolution
Area	BH Urubu River	2640	km²	Magalhães Filho *et al.* (2013)	Sub-basin
Area	BH Dueré River	1054	km²		
BH Urubu River Contribution Area (A)	Cerrado Agriculture Pasture	63.51 4.17 31.7	%	GIS functions **	
BH Dueré River Contribution Area (A)	Cerrado Agriculture Pasture	59.6 3.44 36.8	%	GIS functions **	
Culture Coefficient (Kc)	Cerrado Agriculture Pasture	1 Figure 4 0.9	-	Olivos (2017) Monteiro (2009); Faria *et al.* (2018) Olivos (2017)	Use of the soil
Yield Resistance Factor (RRF)	Cerrado Agriculture Pasture	6 2 4	-	Olivos (2017)	
Top layer field capability (SMax1)	Plintossolo	1000	mm	WEAP*	Soil type
Conductivity in the root zone (Ks)	Plintossolo	1350	mm day-1	Reis *et al.* (2018)	
The preferred direction of flow (f)	Plintossolo	0.15	-	WEAP*	
Relative soil humidity (Z1)	Plintossolo	7	%	Quintino *et al.* (2015)	
Bottom layer capacity (SMax2)	-	1000	mm	WEAP*	Hydrographic basin
Deep layer conductivity rate (Ks2)	-	160	mm day-1	Reis *et al.* (2018)	
Deep layer storage (Z2)	-	54	%	Silva *et al.* (2003)	

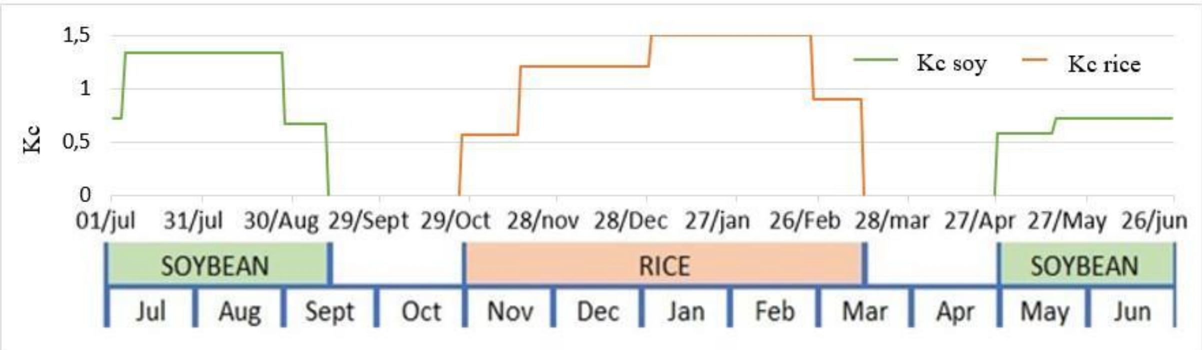

Figure 4. Soybean and rice Crop coefficient (Kc) in the Urubu/TO River Basin.

Table 2. Climate data source used in the streamflow simulation for the reference scenario in the Urubu and Dueré River Basins.

Climate	Unit	Station	Code
Temperature	°C	Lagoa da Confusão	A055
Relative humidity	%	Lagoa da Confusão	A055
Average wind speed	m s-1	Lagoa da Confusão	A055
Fraction of clear sky	%	Porto Nacional	83064

Table 3. Weather stations in the Urubu/TO River basin area.

Station	Code	Responsible	Operator
Lagoa da Confusão	1049003	ANA	CPRM
Dueré	1149000	ANA	CPRM
Poço da Pedra	1149003	ANA	A-N-A
Rio Dueré outlet	26792000	SEMARH-TO	SEMARH-TO
Rio Urubu outlet	26798500	SEMARH-TO	SEMARH-TO
Rio Urubu Fazenda Fortaleza	26795700	SEMARH-TO	SEMARH-TO
Fátima	1048000	ANA	CPRM
Pium	1049001	ANA	CPRM

Calibration performance was evaluated using metrics based on Moriasi *et al.* (2015), defined as the coefficient of determination (R^2), and the Nash-Sutcliffe (NSE) coefficient, both suitable for the daily time scale and the spatial scale of the Formoso River Basin.

After determining the reference flow, the demand impact on the flow of the Urubu River was simulated. Table 4 shows the identification of each irrigation demand hydraulic pump organized in a set of water demand in each water demand node. There were 15 and 16 hydraulic pumps in nodes D1 and D2, respectively, while node D3 represented only 2 pumps, totaling 33 hydraulic pumps. The water withdrawal in this pump was recorded from July 2018 to June 2019. This division was established to represent the withdrawal above the Fazenda Fortaleza fluviometric station (D1), after the station, but before the entrance of the Dueré River to the Urubu River (D2), and after the confluence near the mouth of the Urubu River (D3). Hydraulic pumps belonging to the same farmer received the same identification number, and farms may have abstractions in different stretches of the Urubu River. The irrigation demand data in the model comes from the High-Level Management System (GAN) https://gan.iacuft.org.br/, and so does the daily flow data. The abstractions belong to 21 farmers, some of which have more than one hydraulic pump represented by letters in the identification number (a, b, c and so on).

Table 4. Identification of hydraulic pumps in the Urubu River Basin (TO) WEAP model.

Demand node	Hydraulic pump identification															
D1	1	2	3a	3b	4	5a	5b	6	7a	7b	8	9	10	11	12	-
D2	13a	13b	13c	13d	14a	14b	15	16	17a	17b	18	19a	19b	20a	20b	21a
D3	21b	20c							-							

The daily irrigation demand data in each water pump were input to the WEAP model in the reference (baseline) scenario. Records from 18 water pumps showing less than 10% of failures were averaged to substitute for other missing data in water pumps with flaws in the records. This process separated the whole simulation in three periods as shown in Figure 5 and calculated the average water demand for each of the 18 selected pumps in each period. These values filled in the missing data in all pumps. For the period between harvests, it was considered that there was no water withdrawal, and the gaps were filled with zero. The whole process also observed the schedule defined in the Biennium Plan (IAC, 2018) for water withdrawal in the basin. The total water demand at each node during the simulation period is shown in Figure 6.

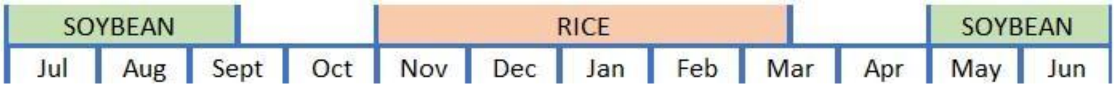

Figure 5. Soybean seed and rice cultivation period considered in this study in the Urubu River Basin/TO.

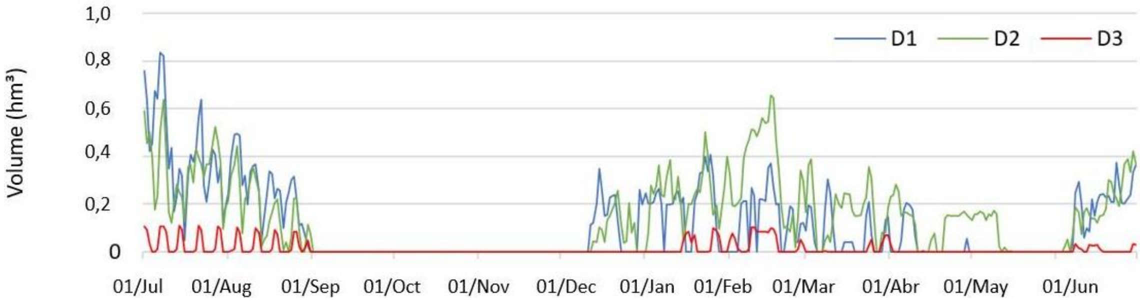

Figure 6. Total irrigation water demand node during the modeling simulation in WEAP (Urubu River Basin/TO).

The WEAP model considers that there may be losses in the water collection and distribution system and that part of this water may be reused internally in the system (SEI, 2016). Thus, Equation 1 computes the flow required for crop irrigation at each water demand node, taking into account losses in the system, internal reuse of water to supply part of the demand, and any technology to use water more efficiently in the system. To consider the actual water demand in the basin, all these parameters and the return flow were set to zero in the Urubu River Basin simulation. The return flow is represented by a percentage of the amount of water that, after being made available for irrigation and not being absorbed by the plants, returns to the river, increasing the availability of water. In this sense, we sought to simulate the most conservative reference scenario.

$$Required = \frac{(Daily\ Demand) * (1 - \%Reuse) * (1 - \%Economy)}{(1 - \%Loss)} \quad (1)$$

The reference or baseline scenario consists of simulated streamflow minus the irrigation water withdrawn from the water demand nodes along the Urubu River, considering both the soybean and rice crops. Based on the reference scenario, three alternative scenarios of demand management were considered and evaluated in terms of the objective to maintain an environmental flow (minimum) in the Urubu River. The study analyzed the reduction of environmental impacts due to high levels of irrigation water demands added to drought events.

The work considered that the alternative scenarios of demand management could result from either the enhancement in the irrigation management practices, the modification of irrigation practices, or the reductions in irrigation network losses, or the selection of alternative crops in the region, especially during the dry season or by anticipating demand through early planting, as long as the sanitary intervals are respected to protect the crops. This study did not focus on proposing the technical solution to be implemented, but on evaluating the required demand reduction to guarantee an environmental flow to protect the ecology and aquatic life in the Urubu River Basin area.

Alternative scenarios were evaluated during the entire year, but since the most critical situation happened between July and August, the analysis concentrated on these months and considered the flows at three sites right after the demand nodes (D1, D2 and D3) in the water resource network built-in WEAP, as shown in Figure 7. The parameters evaluated were the remaining flow after the water demand nodes, the required percentage of demand reduction in order not to interrupt the flow and also to guarantee a minimum flow (1.245 m³ s-1, as indicated in the Report of Phase B of the Diagnosis of Water Demand (IAC, 2017), carried out by the GAN Project team, as possible Q_{90} for the Urubu River in the dry season).

Figure 7. Single-line diagram of demand nodes and analysis points simulated in WEAP (Urubu River Basin/TO).

Scenario 1 considered that all farmers would be able to reduce their water demand by changing the irrigation methods to more efficient and rational choices. Thus, in this scenario, what would be this reduction percentage was evaluated to the point that the Urubu River did not suffer any interruption in its flow and that later it was possible to maintain the flow used as a reference throughout the year. The work evaluated the stream flows in the Urubu River as a result of intervals of a 5% reduction in the water withdraws in all farms. The reduction percentage was applied equally to all water pumps.

Scenario 2 considered the water demand reduction in 90%, 80% and 70% of the water pumps that presented the highest water withdraws aiming in preserving a minimum flow of 1,265 m³ s-1. For this, the percentage of water demand in each farm was calculated as a portion of the total irrigated water demand in the Urubu River. The assessment included all hydraulic pumps belonging to the same property. The division of catchment groups into 90%, 80%, and 70% considered that the farm as a whole would apply measures to increase efficiency. In this way, all pumps on the farm would apply the same percentage reduction in the water volume withdrawal. Table 5 summarizes the water demand management procedures in Scenario 2. The reduction was evaluated every 5% and all demand nodes had hydraulic pumps that reduced demand.

Scenario 3 assesses the impact of anticipating water demand in time. This scenario took into account soybeans for the seed crop period in which there is a sudden decrease in water availability given the beginning of the dry season. The scenario was built on the assumption that anticipating the crop sowing would coincide with a high level of flows in the river, reducing the impact of water withdrawals requiring smaller reductions using efficient practices.

According to farmers in the Urubu River Basin, the starting date to plant soybean crops for seeds occurs on May 1st (IAC, 2017). So this study considered this date as a reference. The Agricultural Defense Agency of Tocantins (ADAPEC) determines that the sowing of soybeans in the lowland regions of Tocantins can only take place from April 20 onwards (ADAPEC, 2016). Thus, Scenario 3 considered the impact of the anticipation of planting by 5 and 10 days. The anticipations were also applied to the period of irrigated rice cultivation. As in Scenario 1, the percentage of water demand reduction was applied to all hydraulic pumps at intervals of 5% reduction.

Table 5. Water demand reduction in Scenario 2 of the Urubu River simulation model in WEAP.

Demand node	Pump ID			Demand representation (%)
	90% of pumps	80% of pumps	70% of pumps	
D2	13a; 13b; 13c; 13d	13a; 13b; 13c; 13d	13a; 13b; 13c; 13d	17.40%
D2	14a; 14b	14a; 14b	14a; 14b	9.40%
D1	7a; 7b	7a; 7b	7a; 7b	8.80%
D2	17a; 17b	17a; 17b	17a; 17b	8.20%
D2/D3	20a; 20b; 20c	20a; 20b; 20c	20a; 20b; 20c	6.60%
D1	10	10	10	5.30%
D2/D3	21a; 21b	21a; 21b	21a; 21b	4.40%
D1	9	9	9	4.30%
D1	6	6	6	4.30%
D1	8	8	8	3.80%
D2	16	16	16	3.60%
D2	19a; 19b	19a; 19b	19a; 19b	3.10%
D1	4	4	4	2.80%
D1	2	2	-	2.70%
D1	1	1	-	2.60%
D2	18	18	-	2.50%
D1	12	12	-	2.50%
D1	5a; 5b	-	-	2.30%

3. RESULTS AND DISCUSSIONS

Table 6 presents the comparison of river basins´ morphometric characteristics considered in the streamflow simulation in WEAP. All sub-basins presented regular drainage density, except the Dueré River Basin. The Compactness Coefficient, the Circulatory Ratio and the Form Factor indicate that all sub-basins tend to present elongated shapes instead of circular preventing floods due to climate extreme events. The drainage density in the Dueré River Basin indicates that this basin is prone to generating quick surface runoff.

Table 6. Morphometric characteristics in the sub-basins.

Sub basins	Urubu River	Dueré River downstream	Fortaleza Farm	Dueré River outlet	Praia Alta
Area (km²)	2630.45	1050.70	2545.90	2502.14	6000.70
Catchment perimeter (km)	319.23	196.61	371.13	383.65	642.21
Main channel (km)	175.70	63.72	144.90	134.11	439.84
All channels (km)	3370.50	926.70	3209.90	4819.60	8793.50
Drainage density	1.28	0.88	1.26	1.93	1.47
Compactness coefficient	1.74	1.70	2.06	2.15	2.32
Circulatory Ratio	0.32	0.34	0.23	0.21	0.18
Form Factor	0.09	0.26	0.12	0.14	0.03

The Plintossolo is the predominant soil type in the area, adding up to the following percentages in the sub-basins: Urubu River (85.2%), Dueré downstream (98.9%), Fortaleza Farm (84.8%), Dueré River outlet (92.2%). This type of soil presents a high probability to generate temporarily flooded areas, especially in plain relief areas that are frequent in the basins. The predominant soil type in the Praia Alta sub-basin is the Latossolo covering 73.3% of the area, indicating better infiltration capacity and faster soil drainage when compared to other basins. Slight portions of Gleissolo, Argissolo and Neossolos of type Quartzarenico and

Litólico are also present in the basin, the two last cited are found only in the Praia Alta Basin.

The study area is predominantly agricultural as shown in the following percentage of agriculture areas in each sub-basin, Urubu River (31.7%), Dueré River downstream (36.8%), Fortaleza Farm (28.6%), Dueré River outlet (40.1%) and Praia Alta (49.6%). The remaining areas in the basins are covered by natural vegetation characteristic of the Cerrado Biome. The predominant slope is classified as plain or slightly undulating, favoring the formation of flooded areas, which is frequent in the Formoso River Basin. The streamflow simulation in WEAP was calibrated using the land use and soil type parameters presented in Table 7.

Table 7. Land use and soil type parameters were considered for the WEAP streamflow calibration.

Parameters	Category	Valor	Unit
Crop coefficient (Kc) Root zone Conductivity (Ks)	Cerrado Plintossolo	10 100	- mm/dia
Runoff resistance factor (RRF)	Cerrado Pastagem	8 6	-
Storage Capacity of the lower layer (SMax2)	-	500	mm

Figure 8 presents the WEAP streamflow calibrated with a good approximation to the regionalized flows. Although the simulated streamflows seemed overestimated at the beginning of the period from September to March, for the rest of the simulation period the calibrated streamflows were close to the regionalized observed data.

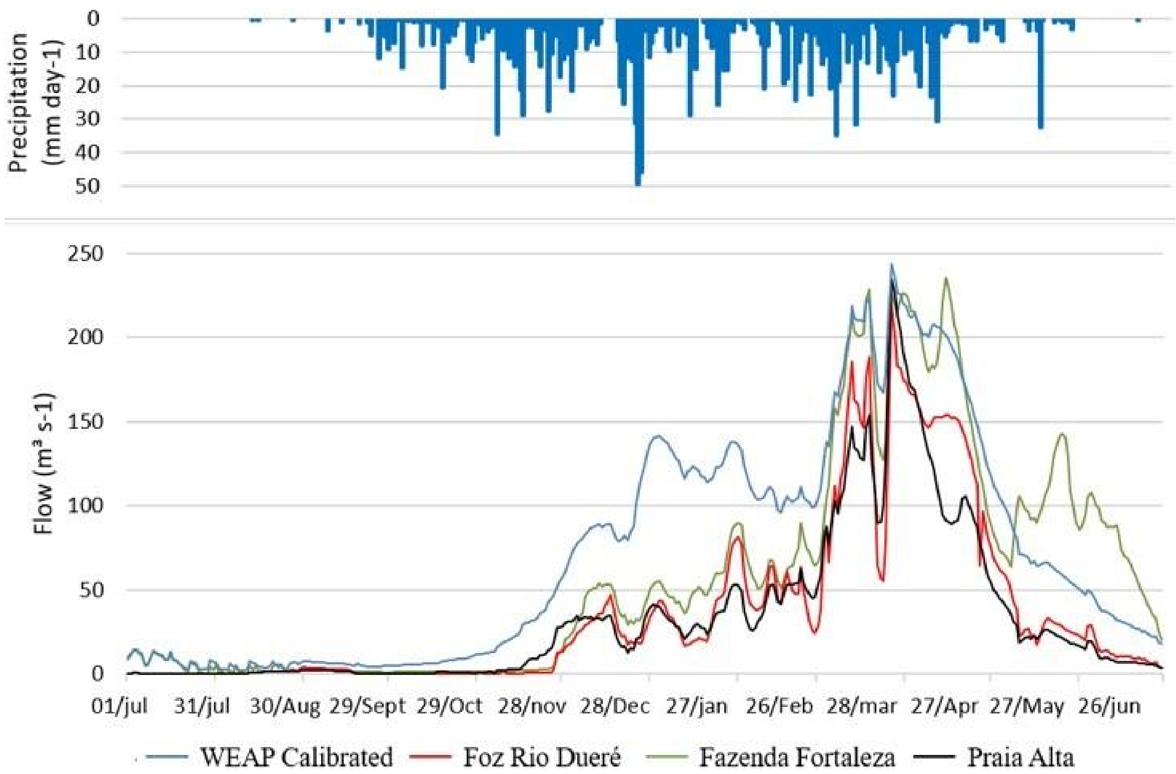

Figure 8. Calibrated Streamflow simulation in WEAP.

Table 8 presents the simulation modeling performance metrics, the coefficient of determination (R^2) and the Nash-Sutcliffe coefficient (NSE). When visually analyzing the flows in Figure 8, it can be seen that they all follow a similar trend despite presenting values in general below the simulated flow, especially for the Praia Alta streamflow gauge in the period from November to February. Since the NSE coefficient is sensitive to extreme values, this may be the reason why the result of the coefficient remains unsatisfactory even after calibration. However, as the other analyses showed improvements and the calibration visibly brought the simulated flow closer to the regionalized ones, the result was considered satisfactory for use as a reference flow in this study.

Table 8. Result of the statistical performance of the flow simulation in the WEAP model compared to regionalized flows.

Streamflow Gauge Stations	R^2				NSE			
	Not Calibrated		Calibrated		Not Calibrated		Calibrated	
Fortaleza Farm	0.63	Satisfactory	0.81	Well	-3.96	Unsatisfactory	0.79	Well
Dueré River outlet	0.65	Satisfactory	0.84	Well	-9.28	Unsatisfactory	0.55	Satisfactory
Praia Alta	0.76	Well	0.89	Very Good	-11.76	Unsatisfactory	0.31	Unsatisfactory

Figure 9 presents the simulation of flows right after the nodes D1, D2 and D3 for the reference scenario and the specific growing season of each of the crops, rice and soybean seed. One can observe that the low flows are critical during the dry season in the Urubu River Basin. Irrigation in this period is mainly associated with soybean for seeds crops sown beginning in May and requires high amounts of water. The high volumes of water demand are not only linked to the plant needs, but also to the predominant irrigation technique applied in the basin, the sub-irrigation by raising the water table. This technique uses large volumes of water, has a low capacity for process optimization, and generates high losses related to water infiltration into the soil. Evaporation in the irrigation channels also influences the water demand, resulting in low irrigation efficiency.

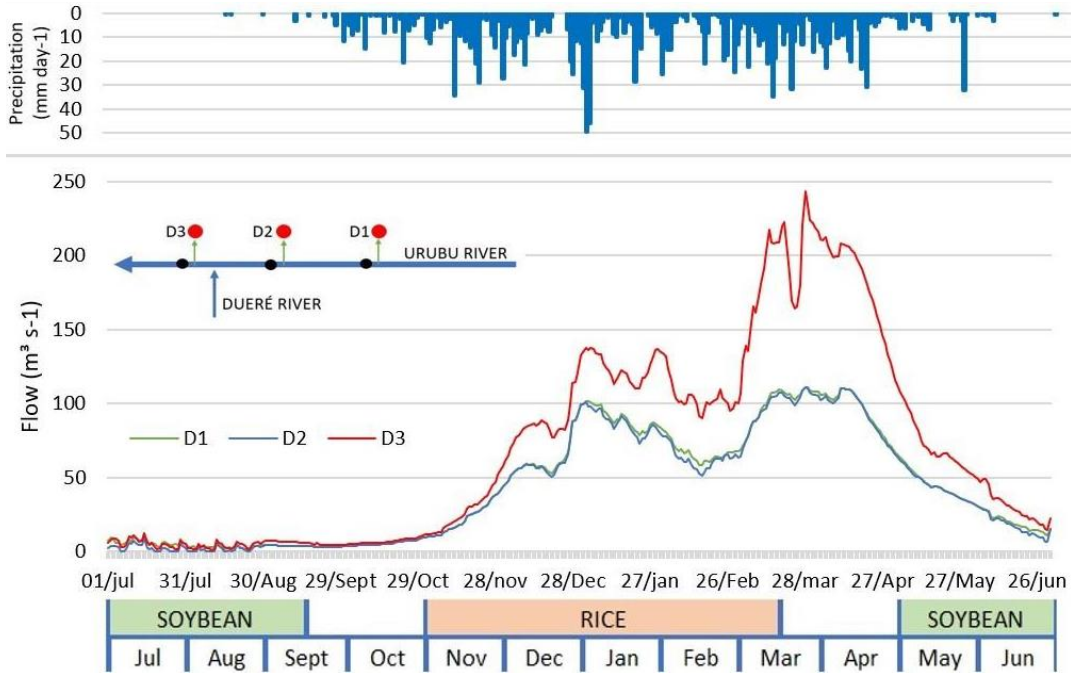

Figure 9. Streamflow simulation after the demand nodes considering the reference scenario (Urubu River Basin/TO).

Figure 9 shows that streamflow volumes after node D3 are higher than the flows after nodes D1 and D2, due to the Dueré River that joins as tributary inflow into the Urubu River, increasing the water availability near its mouth, which is especially relevant in the dry season when soybeans are planted.

Results in the period of rice crop in Figure 9 also showed that, despite the high volume of water withdrawn for irrigation, it does not result in critical flows at any of the analysis points. The greater availability of water during the rice season meant that the impact of water demand was not so significant, especially when compared to the season of soybeans seeds.

Given these initial results, this paper investigated the impact of water demand during part of the dry season, especially between July and August. Figure 10 shows the simulated remaining flows after the demand nodes D1, D2 and D3. Note that flow values after D1 (in the green curve) are already very low, reaching a minimum of 1.67 m³ s-1. This point of analysis is important considering that demand points D2 and D3 will withdraw a high volume of water and the lower the availability observed after node D1, the greater the chances of points D2 and D3 not receiving enough water, triggering water-use conflicts in the region near the basin outlet.

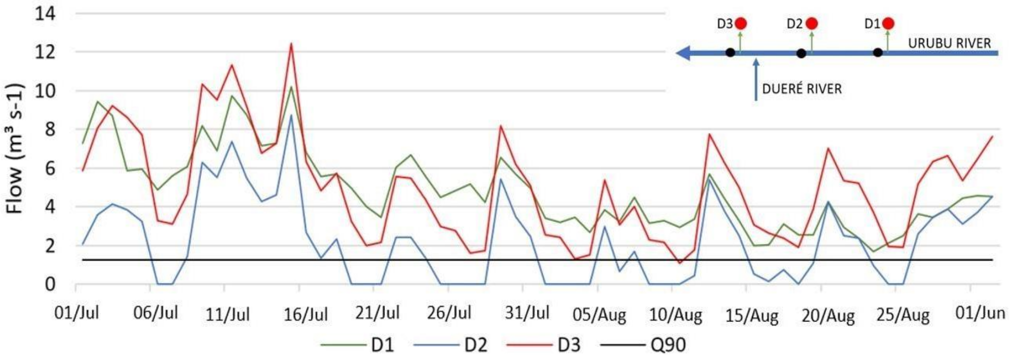

Figure 10. Streamflow during the dry season (July and August) in the Urubu River (TO) after the simulation of demand nodes in WEAP in the reference scenario.

Flows after node D2 were the most critical, as illustrated in Figure 10 in the blue line. At this point, most of the water withdrawals have already taken place and the flow of the Dueré River tributary has not yet been added to the Urubu River. The flows in several points after D2 are down to zero resulting in severe environmental impacts for the region, causing an imbalance to the local ecosystem damaging the biota, making it difficult to return the system to a regular equilibrium. In addition, there are also social and economic damages in the basin, which in turn reflect crop losses due to the lack of water for irrigation.

Also in Figure 10, one can observe that the flow condition after node D3 is much better than in node D2, given the flows coming from the Dueré tributary. However, low flow values are still noted. The analysis at this point is important, considering that the remaining flow will be the inflow to the Formoso River and if this flow is very low or considered insignificant, the crops downstream of the Urubu Basin will also be jeopardized due to propagated impacts in the lower Formoso River Basin.

Given the required reduction in the irrigation water withdrawal observed in the reference scenario of the Urubu River Basin, this research tried to define a minimum percentage of reduction in irrigation water demand that could preserve environmental flows and promote the rational use of water for irrigation in the region. The research evaluated alternative percentages through the simulation of alternative scenarios of irrigation water demands. The focus was to guarantee a minimum flow of 1.245 m³ s-1 (IAC, 2017) in the Urubu River and to avoid the interruption of flow at any point of time during the simulation.

The first alternative scenario took into account that all the irrigators in the basin would apply measures to promote the reduction of water abstraction and, with that, they contributed equally, reaching the same percentage of reduction. Figure 11 shows the remaining flow in the Urubu River after the demand nodes with the application of a 35% reduction in demand, which is the minimum value to guarantee the flows in the river during the simulation period along the main channel. This value was defined by trials adding intervals of 5% reduction until there was no longer a remaining flow equal to zero after the demand nodes.

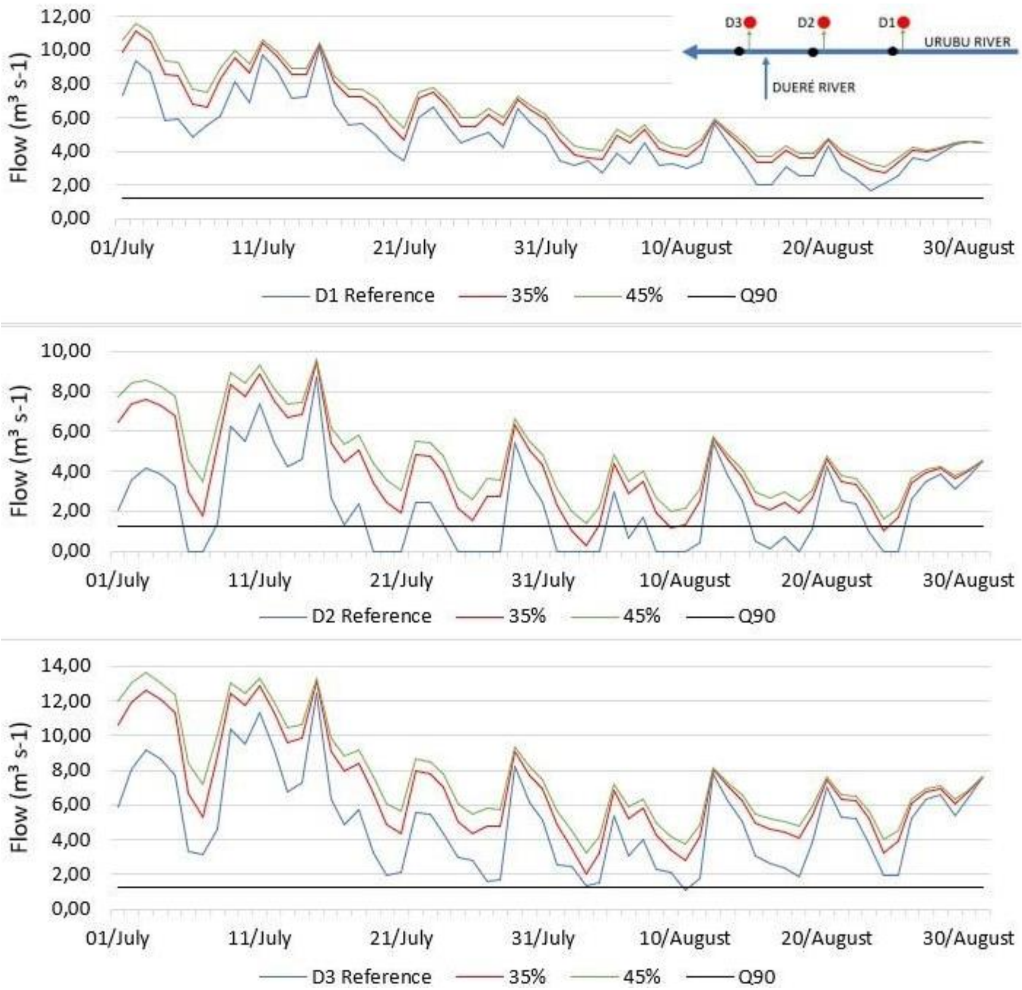

Figure 11. The remaining flow in the Urubu River (TO) after reductions of 35% and 45% was applied to all WEAP simulated abstractions for Scenario 1.

The percentage of 35% reduction is high and difficult to achieve by means of demand management measures or even by increasing the efficiency of the system. Reducing 35% of the water demand in some cases represents reducing a large volume of water and requires high values of investments. On the other hand, the small farmers find it very hard to reduce their demand even more approaching a value that could be harmful to their crops.

It is noteworthy that the reduction aimed at lowering the peaks of flow at the most critical moments, especially after the demand node D2, and that the flow demanded in the analysis period was occurring according to demand rotation rules (IAC, 2018). Thus, peaks in demand could be even more expressive in years when this measure was not applied, resulting in even greater reductions.

With a 35% reduction in demand, despite no interruption in the flow of the Urubu River, the minimum value recorded after node D2 was still very low. In this sense, it was also verified what would be the required reduction so that a minimum flow of 1.245 m³ s-1 in the Urubu River could be guaranteed throughout the simulation period. This water demand reduction should be 45%, as seen in Figure 11, representing a very expressive reduction and, probably, very difficult for farmers to internalize. Considering that the reduction was mainly necessary during the soybean crop, especially from July through August, the demand reduction could actually be applied only during the soybean irrigation, from May through September, maintaining the same values of water demand, without reduction, during the rice season. However, the scenario considered the reduction throughout the simulation period.

The demand reduction established in Scenario 1 demonstrates that the preservation of environmental flows in the Urubu River Basin cannot be based solely on reducing the volumes of irrigation water withdraws according to efforts supported by the farmers themselves. This solution should come from a shared vision among users and public managers. Water-resource managers need to define policies and programs that could benefit the environmental conditions of the drainage system in the basin, protecting the ecosystem services and the economy in the region. Studies that evaluate measures of more sudden changes, revision of the minimum flow values, suspension of grants, or economic evaluation of the benefit/cost ratio of current grants can be carried out to demonstrate the applicability together with the efforts of farmers to achieve environmental conservation in the basin.

The second alternative scenario evaluated the need to reduce the irrigation water demand in the reference scenario so that there would be no interruptions in the flow imposing demand management measures only for users (farmers) of large volumes of water. Figure 12 shows the remaining flow in the Urubu River after the reduction in water demand by 90%, 80%, and 70% of the water pumps. The lowest value of water demand reduction to maintain a minimum flow after irrigation water withdrawals must be 40% for 90% and 80% of the pumps. In this condition, the minimum flow in the Urubu River in the most critical section, located after the demand node D2, would be 0.51 m^3 s-1. The additional 5% reduction of flows compared to Scenario 1 represents an additional pressure on farmers to commit to improving their irrigation system.

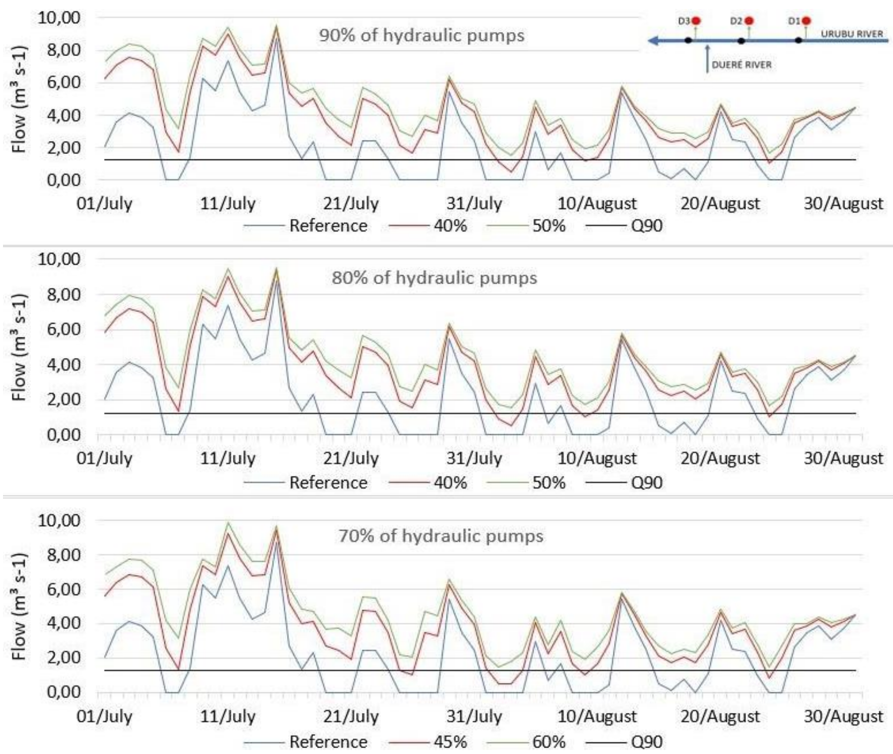

Figure 12. Remaining flow in the Urubu River (TO) after node D2, with an application of demand reduction to 90%, 80%, and 70% of the hydraulic pumps in the WEAP simulations for Scenario 2.

In the most critical situation simulated in the second scenario, in which only 70% of the pumps collecting water for irrigation would reduce the water demand, it would be necessary for them to reach a percentage reduction of at least 45% to avoid the interruption of the water supply, as shown in Figure 12. In this condition, the minimum flow was 0.47 m³ s-1 This reduction is 10% greater than the reduction in Scenario 1.

Maintaining a minimum flow in the Urubu River that is at least equal to 1.245 m³ s-1, the associated effort is very high, reaching a reduction of 50%, equivalent to a remaining flow of 1.52 m³ s-1 when 90 % and 80% of irrigators commit to applying demand reduction measures. The simulated situation is even worse, with the participation of 70% of the irrigators, reaching a reduction of 60% of the reference demand, with a minimum remaining flow equal to 1.46 m³ s-1. These values are unrealistic and will hardly be reached. Furthermore, these values can even discourage a change in irrigation techniques and implementation of more effective methods, as it becomes so complex and costly, in addition to perhaps fostering greater conflicts in the basin, given the non-participation behavior of some irrigators in the face of excessive cost.

The results of Scenario 2, which considered the reduction of irrigation demand is only part of the users ended up overloading them. Thus, the percentage value necessary to maintain a minimum flow in the Urubu River would be even higher than in the first alternative scenario and could be even more expressive, if the irrigators who capture larger volumes of water for irrigation did not apply any demand reduction. The simulation could therefore show an impractical situation with a very relevant socio economic impact, where the other farmers could even have to completely stop water abstraction to maintain the minimum flow in the Urubu River.

Alternative Scenario 3 proposed a combined approach that considers both the planting anticipation and the demand reduction addressed in previous scenarios. This combination proved to be especially advantageous during the dry season when the farmers grow soybeans seeds. The anticipation of demand meant that water withdrawal took place in a period when there was greater availability of water in the Urubu River due to the rainy season or the beginning of the dry season, reducing the impacts of water withdrawal on the remaining flow. This situation was observed in the anticipation of 5 and 10 days, shown in Figure 13. This anticipation had no effect on the rice plantation, given it coincides with the rainy season in the basin.

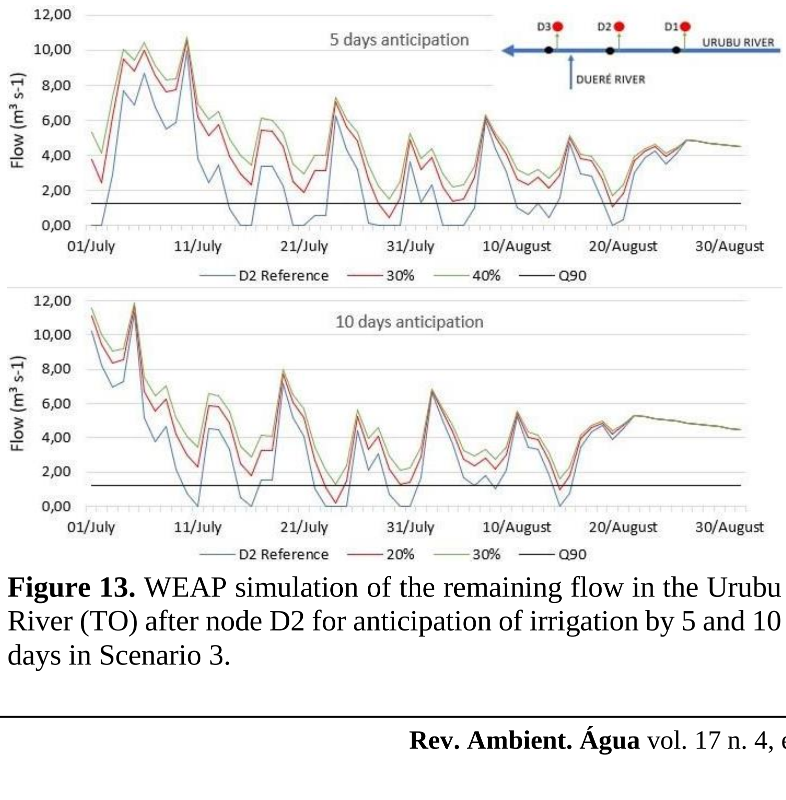

Figure 13. WEAP simulation of the remaining flow in the Urubu River (TO) after node D2 for anticipation of irrigation by 5 and 10 days in Scenario 3.

Figure 13 shows the flows after the demand node D2 and the anticipation of irrigation by 5 days. To avoid the interruption of flow in the Urubu River, it was necessary to apply a 30% reduction in the flow captured in all hydraulic pumps. This reduction made it possible for the lowest remaining flow to be 0.44 m³ s-1, after node D2 at the end of July. Considering the requirement of minimum flow in the Urubu River, the percentage of reduction rose to 40%. In comparison with the first scenario, the reduction associated with the application of more sustainable water management practices decreased by 5%, which favors the farmers and improves this scenario as a possible solution for water-demand management in the Urubu River Basin.

Figure 13 also shows the remaining flow of the Urubu River after node D2 for the anticipation of 10 days and a 20% reduction in the flow captured by all irrigators, so that there would be no interruption in the remaining flow. Despite not interrupting the flow, the minimum value observed was only 0.18 m³ s-1, requiring a reduction rate of 30% to maintain a minimum flow throughout the analysis period. In both cases, the value is 15% lower than in the first scenario, which highlights the importance of all farmers working together, combined with a planting practice that is aligned with the natural cycle of water availability. The combination of these two demand management measures can increase the performance of local agriculture, reducing socio-environmental conflicts and environmental and economic damage caused by water shortage.

Table 9 summarizes the minimum water demand reductions required in all scenarios in order to preserve the streamflow in the Urubu River and also the minimum water demand reduction in order to maintain the environmental streamflow defined as 1.245 m³ s-1.

Table 9. Necessary demand reduction results for each alternative scenario simulated.

Scenario	Scenario Condition	Minimum Demand Reduction	Minimum Demand Reduction to Maintain 1.245 m³ s-1
Scenario 1	All hydraulic pumps	35%	45%
Scenario 2	90% of hydraulic pumps	40%	50%
	80% of hydraulic pumps	40%	50%
	70% of hydraulic pumps	45%	60%
Scenario 3	Demand anticipation in 5 days	30%	40%
	Demand anticipation in 10 days	20%	30%

The results in the simulation show the importance of water demand management measures to irrigation efficiency in the Urubu River Basin. These efforts also reduce the environmental impacts associated with ecological systems. Water demand reduction may be achieved by means of controlling water losses in the transport channels to the plantation areas, changing the method of sub-irrigation by technologies that promote rational water use, selecting crops that may be less water-demanding or be more adapted to dry seasons. According to the results of the alternative scenarios, it is important that all farmers in the basin cooperate actively and contribute to these efforts.

One should not forget the important role of water institutions and managers in the region once they could enhance monitoring, regulation and enforcement contributing to the security of water systems in the basin especially during droughts. Thus, measures such as modifying water permits during droughts events, planning and scheduling water-use restriction when necessary, and considering the application of a collective permit can help in the management of water resources in the Urubu River Basin. The High-Level Management Project (GAN) has also proved to be extremely important to increase knowledge about water availability and demand in the region of the river basin of the Formoso River. The project allowed the installation of flow meters in all hydraulic pumps in the basin contributing to enhancing the water regulation and monitoring in the region, allowing the selection of management measures and practices to improve the water resources security in the Formoso River Basin.

4. CONCLUSIONS

The Urubu River Basin is an important agricultural area for the state of the Tocantins, North of Brazil. The basin has faced water shortage due to a combination of factors, years of low levels of rainfall and high irrigation water demand, especially associated with soybean crops during the dry season (July and August). First, the work evaluated the WEAP hydrological modeling to obtain a reference flow for the Urubu River and part of the Dueré River, using the Rainfall Runoff method in WEAP. The analysis of the statistical performance results for the calibrated flows was Very Good (R^2) and Good (NSE).

The second stage of this work simulated the water balance in the Urubu River Basin using the WEAP model for a reference scenario including all of the irrigation water demand sites and evaluated the effect of alternative irrigation water demand management scenarios in the Urubu River Basin. The alternative scenarios were analyzed considering the objective to avoid environmental and economic impacts due to low levels of flow in the main channel. The unsustainable irrigation water demand in the region has proved to be a reflection of an inefficient irrigation system that jeopardizes aquatic life and economic activities in the Urubu River Basin.

In an ideal situation in where all farmers contribute and modernize their irrigation system, resulting in lower irrigation water demand (Scenario 1 - equal percentage reduction for all), the required demand reduction would be 35%, so that the river did not suffer any interruption of the flow rate and 45% to maintain at least 1,245m³ s-1 at all times. The reduction is even greater when compared to Scenario 2, in which the simulation considered that part of the farmers did not contribute to the irrigation water demand reduction. For this condition, reductions of 40% and 45% were necessary, when 10% and 30%, respectively of the irrigators did not contribute to the demand management measures.

Finally, Scenario 3 illustrates that combining water demand reduction with anticipation of crop sowing (10 and 5 days) and observing agriculture sanitary regulations could be a good strategy for streamflow conservation in the Urubu River Basin. The alternative scenarios also showed that the active participation of all irrigators is essential to reduce conflicts and environmental impacts in the basin. It is also important to emphasize that the application of hydrological models to expand the knowledge of the water balance in a basin and analyze different scenarios, proved to be an important tool enabling the illustration of benefits from robust water demand policies and management in the basin.

The analysis highlighted the importance of water demand management practices in the Urubu River Basin, such as efficient and rational irrigation techniques, reduction of water losses in the irrigation network and channels, and selection of crops more adapted to the dry season. These practices should be adopted by all irrigators so that they do not overload only part of the farmers in the region, reducing the emergence of conflicts and making it possible to implement adequate water demand management in the region.

The simulation of the water balance in the Urubu River Basin presented challenges regarding the availability of data. Thus, the importance of hydrological monitoring and its expansion in the Formoso River Basin is also emphasized showing the benefits of research projects, such as the High-Level Management Project (GAN). The future use of these historical series with greater consistency may contribute to better management of water resources, strengthening the balance between environment and economic activities. It is also noteworthy that with the greater availability of data in the future, the results of the present research should be reevaluated to confirm and evolve the water management practices in the basin.

5. ACKNOWLEDGEMENTS

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