Revista Brasileira de Recursos Hídricos
Brazilian Journal of Water Resources
Versão On-line ISSN 2318-0331
RBRH, Porto Alegre, v. 29, e13, 2024
Scientific/Technical Article

https://doi.org/10.1590/2318-0331.292420230092

Evaluation of collective water rights allocation scenarios using the WEAP simulation model in a region of water use conflicts: the case of Formoso River Basin – Tocantins state/Brazil

Avaliação de cenários de alocação coletiva de direitos à água utilizando o modelo de simulação WEAP em regiões de conflito pelo uso da água: o caso da Bacia do Rio Formoso-Tocantins/Brasil

Eduardo Paulino da Silva[1], Ricardo Tezini Minoti[1], Conceição de Maria Albuquerque Alves[1], Nicole John Volken[1] & Fernan Enrique Vergara Figueroa[2]

[1]Universidade de Brasília, DF, Brasil
[2]Universidade Federal do Tocantins, Palmas, TO, Brasil

E-mails: eduardopaulino_silva@hotmail.com (EPS), calves@unb.br (CMAA), nicolejvolken@gmail.com (NJV), vergara@mail.uft.edu.br (FEVF), rtminoti@unb.br (RTM)

Received: September 01, 2023 - Revised: December 26, 2023 - Accepted: March 19, 2024

ABSTRACT

The aim of the present study was to carry out a hydrological simulation of the Formoso River basin using WEAP and to model scenarios based on the rotating rules of the water pump in regions of conflict for the use of water. During July 2020, the influence of such rules on the remaining flow in these regions was assessed considering a collective grant context in which minimum environmental flows, determined from the seasonal Q90 (flexible) and monthly Q95 (conservative), should be preserved downstream from the critical sections. The results showed that the remaining flow exceeded the limit of the flexible environmental flow in 61% of the days in the middle stretch of the Formoso River and at the mouth of the Urubu River. In the lower section and mouth of the Formoso River, these values were above the conservative limit in 93% and 100% of the days, respectively. It was concluded that the application of the rules, coupled with the collective grant, could produce satisfactory results for water availability in the basin.

Keywords: WEAP; collective grant; Formoso River Basin.

RESUMO

O presente estudo teve como objetivo realizar a simulação hidrológica da bacia do Rio Formoso por meio do WEAP e modelar, nas regiões de conflito pelo uso da água, cenários baseados em regras de rodízio das bombas de captação d'água. Avaliou-se durante o mês de julho de 2020 a influência de tais regras sobre a vazão remanescente nessas regiões, considerando um contexto de outorga coletiva, em que vazões ambientais mínimas, determinadas a partir da Q90 sazonal (flexível) e Q95 mensal (conservador), devem ser preservadas a jusante dos trechos críticos. Os resultados mostraram que no médio trecho do rio Formoso e na foz do rio Urubu a vazão remanescente supera o limite de vazão ambiental flexível em 61% dos dias. No baixo trecho e na foz do rio Formoso, esses valores são superiores ao limite conservador em 93% e 100% dos dias, respectivamente. Conclui-se que a aplicação das regras, associadas à outorga coletiva, podem produzir resultados satisfatórios para a disponibilidade hídrica na bacia

Palavras-chave: WEAP; outorga coletiva; Bacia do Rio Formoso.

INTRODUCTION

The granting of water use rights is an important instrument in Brazil's National Water Resources Policy, created to ensure the control of the quantity and quality of water uses as well as the effective implementation of access rights to this resource. However, owing to the difficulties associated with the application of this instrument in complex regions where there are conflicts over water use, managers have sought regulatory alternatives suited to local peculiarities.

In recent years, the application of a variant of the granting instrument has strengthened the state's capacity in regions where conflicts over water use occur, mainly through the effective and direct participation of users in the management of water resources. This instrument is a collective grant.

The term 'collective grant' does not appear in any legal text but is used by the National Water and Basic Sanitation Agency (ANA) to refer to an act of granting authority where several users and their respective uses of water resources are granted. The collective grant from the Negotiated Allocation of Water represents one of the situations of application of the collective grant, where a group of users undertakes to use a maximum flow defined in a negotiation process (Agência Nacional de Águas e Saneamento Básico, 2011, 2013).

According to Spolidorio (2017), the application of negotiated allocation, effectively linked to participatory processes and collective grants, can strengthen the state's capacity because, in addition to relying on the contribution of water users who are directly interested in the process, it can also benefit from the creation of environments of true regulation between users, as strongly observed in basins where water scarcity is present.

In these water allocation negotiation scenarios, the use of hydrological models as decision support tools in the planning and management of water resources, such as WEAP, is fundamental because they can provide information related to demand and water availability as well as evaluate, through alternative hypotheses, the impact of new policies and regulatory approaches on available resources.

The WEAP model has been used to evaluate systems in water stress scenarios and in the reformulation of policies aimed at the management of water resources. Zehtabian et al. (2023) developed a water resources management model with the aim of improving water management in the Gavkhouni basin, which suffers from scarcity and unmet water demands, especially with regard to environmental demands. This study created seven possible management scenarios in WEAP and subsequently selected the best evaluated scenario for application in the study area.

Notisso (2020) evaluated the ability to satisfy water needs in the Inhanombe basin in Mozambique using WEAP to simulate impact scenarios corresponding to the expansion of the irrigated area and population growth between 2019 and 2040. The results showed the inability of the system to meet future needs for the evaluated period with low levels of monthly guarantees and many supply failures.

Reis et al. (2020) evaluated the contribution flows of the hydrographic basin from the Grande River to the São Francisco River in Brazil, considering the multiple uses of water stored in the Sobradinho reservoir. The minimum flows delivered by the Grande River to the São Francisco River channel were evaluated based on the simulation of alternatives for prioritizing water demands through WEAP. The study showed that the flows of tributary rivers to the main river are important for meeting the various water demands in the region.

The objective of this study was to investigate the watershed of the Formoso River, located in the southwest portion of the state of Tocantins, Brazil, a very important area for agricultural production. According to the IAC (Instituto de Atenção às Cidades, 2018), this basin is characterized by conflicts over the use of water that occurs during the dry period (May to November) between farmers who carry out irrigation activities and collect water from rivers using hydraulic pumps. In June 2016, two important rivers in the basin, the Urubu and Formoso, experienced severe reductions in water volume, leading to judicial intervention.

Faced with this situation, the Institute for Attention to Cities (IAC), linked to the Federal University of Tocantins (UFT), developed the High-Level Management Project (GAN), which implements a series of measures to improve the management of water resources in the basin. Although the positive results have been expressive, the last phase of the project, related to the review of grants and the definition of pump operation rules, has not been concluded. This phase is fundamental, because inconsistencies were identified in the application of the granting instrument in the region.

Consequently, a Working Group (WG) was created in 2018 to prepare a document on the operational organization of funding, especially during the critical period. This document was named the 2018–2019 Biennium Plan. One of the proposals provided in this document is the application of rotation rules to intake pumps during the dry period, to mitigate the effects of water scarcity in the region. However, these rules have not been implemented in the basin.

Thus, this study proposes to carry out a hydrological simulation of the FRB using WEAP and model management scenarios in the basin's conflict areas, considering the operating rules of the intake pumps established by the Biennium Plan. This study also examined the influence of these rules on the remaining flow in the context of collective granting, in which users must commit to a minimum environmental flow to be maintained downstream of the critical stretches.

MATERIAL AND METHODS

Study area

According to SRHMA (Secretaria de Recursos Hídricos e Meio Ambiente do Tocantins, 2007), the FRB is located in the southwestern portion of the state of Tocantins. It has a drainage area of 21,328.57 km^2, approximately 7.7% of the total area of the state and 5.6% of the Araguaia River basin, covering 21 municipalities, of which, for reasons of planning and water resource management, six are disregarded, either because they are municipalities in Goiás and represent a very small portion of the total area of the basin, or because they are municipalities in Tocantins that only border the watershed. For studies on anthropic, legal, institutional, and water resource management, 15 municipalities were recognized as members of the basin. These results are shown in Figure 1.

Physical characterization

According to the application of the Thornthwaite method, FRB presents a humid climate with a variation in water deficit from moderate to zero and potential evapotranspiration varying, on average, from 1400 to 1700 mm. In summer, the period of three months with the highest temperature, ranged from 390 to 500 mm. With regard to precipitation and temperature, the average annual accumulated rainfall ranges from 1500 to 1900 mm, whereas the compensated average annual temperature ranges from 25 to 26°C (Secretaria de Recursos Hídricos e Meio Ambiente do Tocantins, 2007; Secretaria de Planejamento e Orçamento, 2017).

Regarding the relief of the FRB, Alves et al. (2015) characterized the region as predominantly composed of the flat class, which represents 32% of the total area of the basin and is located in the middle and lower courses of the Formoso River, where the main areas of irrigated agriculture are located, with emphasis on the Formoso River Project. In the upper course of this river (the south region of the BHRF), smooth-wavy and wavy relief classes prevail, occupying 36.4% and 29.4% of the region, respectively. The remaining 2.2% represent the Strong Wavy class that occasionally occurs in some regions of the basin.

The classes of soils that predominate in the study area, in decreasing order of extension, are Concretionary Soils (40.8%), Red-Yellow Latosol (33.0%), Plinthosol (15.0%), Gleized Hydromorphic (7.0%), and Red-Yellow Podzolic (3.5%). Quartz sand (0.5%) and Litholic Soils (0.1%) have a very restricted occurrence and exist only in the Escuro River subbasin (Secretaria de Recursos Hídricos e Meio Ambiente do Tocantins, 2007).

Plinthosols are important in irrigated agriculture and pastures. According to IBGE (Instituto Brasileiro de Geografia e Estatística, 2007), FRB projects for grain cultivation and annual fruit growth are installed on haplic plinthosols, whose characteristics require very delicate agricultural management and good control of their internal water dynamics. In contrast, concretionary soils are used for extensive grazing in areas of grassland or Cerrado vegetation or pasture planted with rustic forage species.

The basis of the FRB economy is the agricultural sector, which supports other sectors related to primary activity. The municipalities of FRB induced quite high percentages with the state collection, mainly Formoso do Araguaia and Lagoa da Confusion, and are in a favorable environment for agricultural production, especially irrigation, owing to water availability and topography. The Formoso Project is located in Formoso do Araguaia, the largest irrigated rice project in the world on continuous land, covering approximately 27,787 ha. Other municipalities have private properties that use irrigated agriculture (Companhia Nacional de Abastecimento, 2015; Secretaria de Recursos Hídricos e Meio Ambiente do Tocantins, 2007).

According to the IAC (Instituto de Atenção às Cidades, 2018), the FRB is marked by two distinct periods with regard to water availability: the rainy period, which comprises the months of December to April, and the dry period, which comprises the months of May to November, where there is an abrupt reduction in river flow. According to SHRMA (Secretaria de Recursos Hídricos e Meio Ambiente do Tocantins, 2007), this situation is associated with the peculiar characteristics of the soils in the region, mainly plinthosol, in addition to the different crops that can be exploited in this situation, which allows the use of the same area with two crops throughout the year.

In the rainy season, the plinthosols are soaked, as they occupy the lower elevations of the land in flat relief, allowing only the cultivation of rice irrigated by flooding because of their

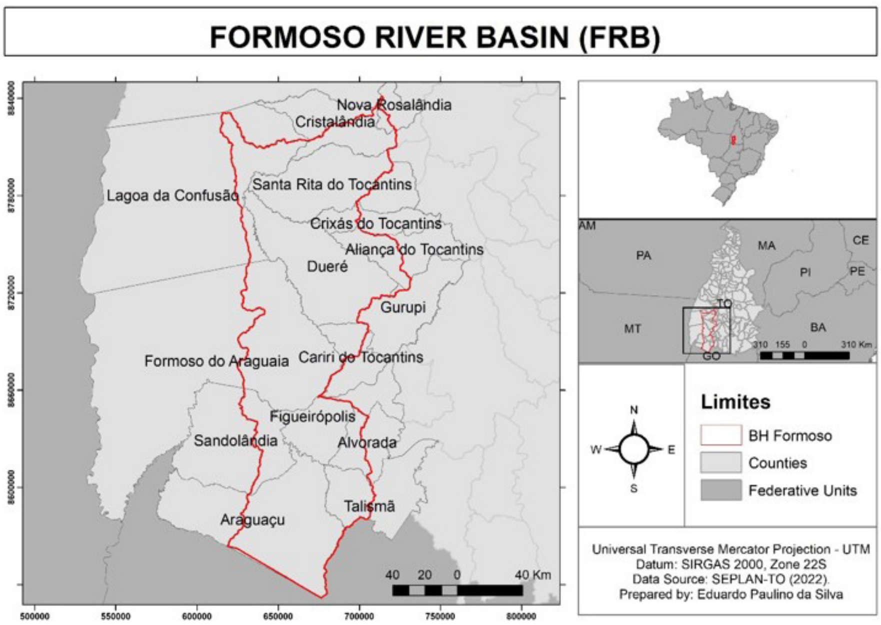

Figure 1. Formoso River Basin (FRB) and municipalities contours.

hydrophilic characteristics. During the dry period of the year, with water availability, several crops can be explored in the same area as plinthosols, such as soybeans, corn, beans, watermelon, melon, and tomato. In this case, owing to the peculiar characteristics of the soils, sub-irrigation was carried out; that is, the water was kept in the channels and drains of the crop, raising the water table and allowing the rise of moisture by capillarity to the area where it is located determines the root system of the crops (Secretaria de Recursos Hídricos e Meio Ambiente do Tocantins, 2007).

In recent years, the scarcity of water resources in FRB has led to conflict over the use of water during the dry period. According to the IAC (Instituto de Atenção às Cidades, 2018), this is related to a sharp reduction in water availability, which is characteristic of the period associated with high water consumption. In addition, the IAC (Instituto de Atenção às Cidades, 2017a) assessed that the surface collection pumps that feed irrigated agriculture developed in the region are poorly distributed along the FRB, with a high concentration of pumps in small stretches of some rivers in the basin.

Biennium Plan 2018-2019

According to the IAC (Instituto de Atenção às Cidades, 2018), the Biennium Plan presents the operational organization of the surface collection pumps along the FRB rivers, especially in the dry period, to anticipate the established criteria, enable producers to plan, and allow managers to operate preventively and not just reactively to problems after they occur. Three pump operating rules, called traffic light rules, were established based on the Minimum Reference Levels or months of the dry period.

According to the IAC (Instituto de Atenção às Cidades, 2018), when river levels are higher than the level of attention, abstraction takes place in accordance with the grants issued by each intervention (green rule). However, on July 1st, or when these levels reached the attention level, two pump rotation alternatives, Scenarios A and B, were proposed to come into effect. During this period, the pumps were divided into three groups and subjected to weekly rotation rules. Grouping is performed such that the number of pumps and the total flows of each group reflect a balanced distribution for the safe management of water resources.

On August 1st, or when the river levels reach a critical level, all surface abstractions are suspended until November 1st (red rule). To evaluate the effect of these rules on water availability in critical sections, after calibrating the FRB model in WEAP, Scenarios PB-A and PB-B were modeled in July 2020. The Formoso River basin is characterized by two well-defined seasons, one of which is dry, extending from May to November, the choice of year does not affect the analysis of the flow after the implementation of the rules.

Data base

FRB modeling was carried out for the period starting on July 1, 2018 and extending until June 30, 2021, considering a daily time step. The system tracks water demand and availability data as well as data related to climate variables, which are necessary for simulating hydrological processes in WEAP.

The water demand data, corresponding to the daily volumes of water (m^3) captured by the water pumps, were acquired from the online application of the High Level Management Project (GAN), a robust water resource management system developed by the Federal University of Tocantins, which features a publicly accessible database with daily historical series on abstraction (average flows, volumes, period of operation, and amounts charged for water use), obtained from the monitoring of pumps in the region, which are updated every 15 min.

Water availability data, referring to the daily historical series of river flows (m^3/s), were obtained from the HidroWeb portal, a tool that is part of the National Water Resources System (SNIRH), which offers access to a database containing all the information collected by the National Hydrometeorological Network (RHN). The that were used stations are listed in Table 1. The responsibility and/or operation of these stations belongs to the National Water and Sanitation Agency (ANA), Mineral Resources Research Company (CPRM) and the Secretariat of Environment and Water Resources (SEMAR- TO).

The stations presented in Table 1 were chosen because they were located close to the critical sections, which allowed the evaluation of the remaining flow during the analysis of the modeled scenarios. Owing to the presence of gaps in their respective historical series, they were subjected to gap filling using two methods: regionalization of flows and multiple linear regression.

The climatological variables required by WEAP are: Total Precipitation (mm), temperature (°C), humidity (%), Wind Speed (m/s), Cloud Fraction, and Albedo. Precipitation data were obtained from rain gauge and telemetric stations of the National Water and Sanitation Agency (ANA). Using these data, the average precipitation in each sub-basin was determined by applying Thiessen's Polygon Method.

Temperature, Humidity, Wind Speed, and Cloud Fraction data were acquired from automatic stations of the National Institute of Meteorology (INMET). Owing to the presence of failures in the historical series of the first three variables, a multiple linear regression model was applied to fill in the days without data, prioritizing the equations with the highest coefficients of determination (R^2).

The historical albedo series was extracted from the NASA POWER website (Prediction of Worldwide Energy Resources), which provides important data for the studying of climate and

Table 1. Fluviometric stations selected for modeling in WEAP.

Station	Code	Responsible	Operator	Lat (°)	Long(°)
Projeto Rio Formoso	26730000	ANA	CPRM	-11.8392	-49.7711
Foz Rio Formoso	26799000	SEMARH-TO	SEMARH-TO	-10.5856	-49.9264
Foz Rio Urubu	26798500	SEMARH-TO	SEMARH-TO	-10.8278	-49.7956

climate processes through satellite systems. Figure 2 shows the spatial distribution of the rain gauge, telemetric, and meteorological stations used in this study.

Modeling in WEAP

The Water Evaluation And Planning System, known as WEAP, is a practical tool for water resources management, planning, and policy analysis that incorporates an integrated view of water resource development as it puts water supply projects in the context of demand management, water quality, and the preservation and protection of ecosystems (Stockholm Environment Institute, 2015, 2023).

Created by the Stockholm Environment Institute (SEI), this tool operates based on the principle of water balance accounting and is applicable to municipal and agricultural systems, single sub-basins, or complex river systems. It can address a wide range of issues such as sectoral demand analysis, water conservation, water rights and allocation priority, groundwater and flow simulations, reservoir operation, hydropower generation and energy demands, pollution tracking, ecosystem requirements, and cost-benefit analyses of the project (Sieber, 2006; Stockholm Environment Institute, 2015).

Structure

According to SEI (Stockholm Environment Institute, 2015), WEAP is structured as a set of five different ways of "visualizing" a water system. They are: Schematic, Data, Results, Scenario Explorer, and Notes. In the tool, these views are listed as graphic icons in the view bar located on the left side of the screen, as shown in Figure 3.

Schematic is the starting point for all activities in WEAP. The structure of the model is defined using entities (nodes) and their connections (arcs). Nodes indicate elements such as demand points, reservoirs, river basins, water treatment plants, underground aquifers, river gauge stations, and flow requirements. Arcs establish connections between nodes and represent rivers, transmission links, diversions, surface flows, and return flows. Each node and arc have an associated mass balance equation and, in some cases, additional flow restriction equations (Stockholm Environment Institute, 2015; Fard & Sarjoughian, 2021).

In the Data, it is possible to create, for each of the elements (nodes and arcs) established in Schematic, variables and relationships, assumptions and projections using mathematical expressions, in addition to linking external files, such as CSV or Excel data files (Kirilov & Bournaski, 2019; Fard & Sarjoughian, 2021).

The Results view is used to choose the simulation outputs to be extracted and visualized in graphs, tables, and the Schematic Map. Additionally, different entities, scenarios, years, and units can be used as graphs displaying varying values for the time intervals. Data can be filtered for a detailed and flexible display of model input and output data values for time step trajectories (Fard & Sarjoughian, 2021).

Finally, the Scenario Explorer and Notes views played an auxiliary role in building the model and analyzing the results. According to SEI (Stockholm Environment Institute, 2015), while

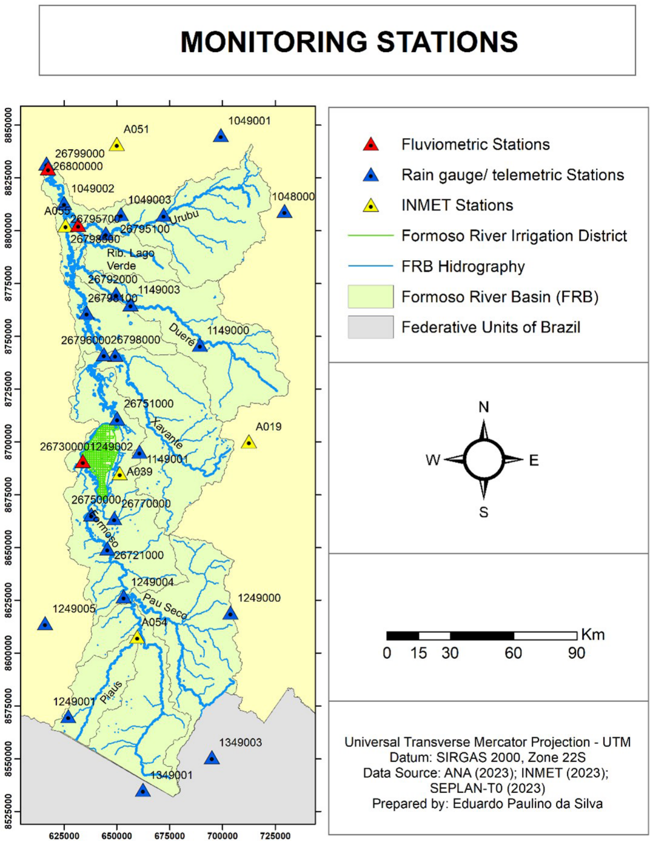

Figure 2. Spatial distribution of fluviometric, telemetric and meteorological stations used in FRB modeling in WEAP.

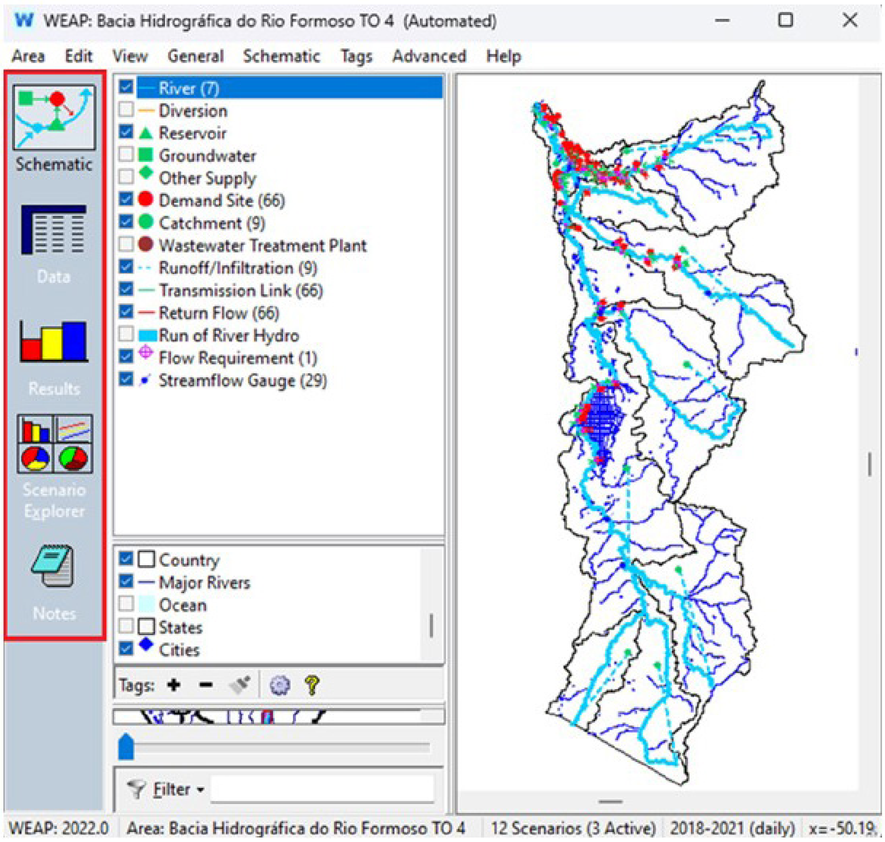

Figure 3. Layout of the WEAP tool and representation of the FRB in Schematic.

Scenario Explorer highlights the main data and results in its system for quick visualization, in Notes, it is possible to document data and assumptions.

Soil moisture method

The simulation of processes in watersheds, such as evapotranspiration, runoff, infiltration, and irrigation demand, can be performed using five methods coupled with WEAP: rainfall runoff, irrigation demands only, rainfall runoff, the MABIA method and the plant growth method (Stockholm Environment Institute, 2015; Opere et al., 2022).

The FRB simulation in WEAP was performed using Rainfall Runoff application (Soil Moisture Method). This choice is quite pertinent, bearing in mind the peculiar characteristics of the soil in the region, which change according to seasonality throughout the year and strongly influence the water availability for irrigated agriculture.

The Soil Moisture Method was formulated based on a one-dimensional conceptual model algorithm that represents a watershed with two layers of soil, where evapotranspiration was simulated in the upper layer, considering precipitation and irrigation in agricultural and non-agricultural lands, surface and subsurface runoff, and changes in soil moisture. This method allowed us to characterize the impacts of land use and/or soil type on these processes. In the lower layer, base flow and changes in soil moisture were simulated (Stockholm Environment Institute, 2015; Teklu et al., 2020).

A one-dimensional conceptual model of the Soil Moisture Method is shown in Figure 4. The mass balance of the upper and lower layers of the soil obeyed Equations 1 and 2, respectively.

$$R_{d\,j}\frac{d_{z1,j}}{dt} = P_e(t) - PET(t)k_{c,j}(t)\left(\frac{5z_{1,j} - 2z^2_{1,j}}{3}\right) - P_e(t)z_{i,j}^{RRF_j} - f_j k_{s,j} z_{1,j}^2 - \left(1 - f_j\right)k_{s,j} z_{1,j}^2 \quad (1)$$

- Pe: Effective precipitation (mm)
- kc,j: Crop coefficient for each fraction of land j.
- PET (t): Potential or Reference Evapotranspiration (mm/day)
- z1,j: Relative storage (%), given as a fraction of the total root zone effective storage, for the land cover fraction, j.
- RRF: Land Cover Runoff Resistance Factor
- ks,j: root zone saturated hydraulic conductivity (mm/time)
- fj: partitioning coefficient related to soil, land cover type, and topography that fractionally partitions water horizontally and vertically.

$$S_{máx}\frac{dz_2}{dt} = \left(\sum_{j=1}^{N}\left(1 - f_j\right)k_{s,j} z_{1,j}^2\right) - k_{s2} z_2^2 \quad (2)$$

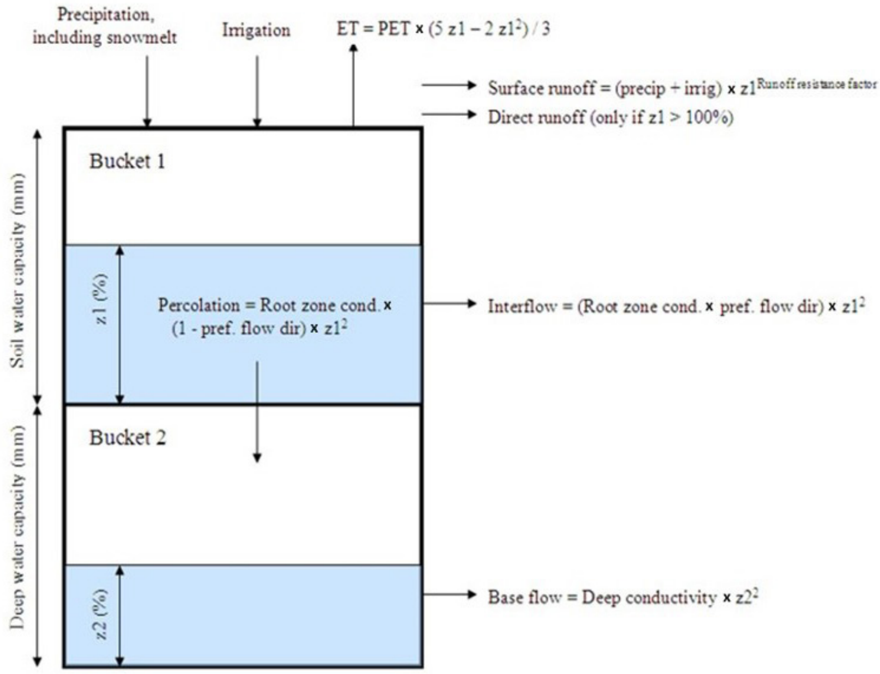

Figure 4. Conceptual diagram and equations incorporated in the Soil Moisture Method.

• $Smáx$: Maximum storage in the deep layer
• $z2$: Relative storage (%) given as a fraction of the maximum deep layer storage.
• $dz2dt$: Variation in relative storage z2 as a function of time t.
• $ks2$: saturated conductivity in the lower layer (mm/time)

Sensitivity analysis

Sensitivity analysis in WEAP was performed by evaluating the influence of each soil variable on the average flow results for the entire modeling period. Before each execution of the model, the value of the analyzed variable was changed, keeping the standard values established for the others. The Sensitivity Index (SI) proposed by Nearing et al. (1990) is given by Equation 3:

$$IS = \frac{\frac{O_1 - O_2}{O_{12}}}{\frac{I_1 - I_2}{I_{12}}} \tag{3}$$

where, in the numerator, **O1** and **O2** indicate, respectively, the result obtained by the model with the lowest and highest input value, while **O12** is the arithmetic mean of these two results. In the denominator, **I1** and **I2** are the smallest and largest model input values, respectively, and **I12** is the arithmetic mean of I1 and I2.

The SI value represents the normalized change generated in the model output for the normalized change in the input data. The higher the indices are, the more sensitive the model is to the parameter, whereas values close to zero indicate that the model is insensitive. The SI sign indicates the relationship between the input value and result; negative values indicate that the input value and result are inversely proportional, whereas positive values indicate that they are directly proportional (Silva et al., 2009).

Model calibration

The SI results obtained from the sensitivity analysis guided the calibration of the FRB model. This process was performed manually by modifying the soil parameters of the Soil Moisture Method based on their standard values. These parameters, shown in Table 2, are the Crop Coefficient – kc, Soil Water Capacity – SWC (mm), Deep Water Capacity – DWC (mm), Runoff Resistance Factor - RRF, Root Zone Conductivity – RZC (mm/day), Deep Conductivity – DC (mm/day), Preferred Flow Direction - PFD and Initial Z1 and Z2 values.

The quality of the adjustments was evaluated by calculating three statistics: the efficiency of Nash-Sutcliffe (NSE), the Percent BIAS (BIAS), and the Coefficient of Determination (R^2). Table 3 presents the Performance Evaluation Criteria for the performance measures of these statistics for watershed-scale models as recommended by Moriasi et al. (2015).

Scenario definition

The scenarios designed to be simulated in WEAP after model calibration were based on the application of water pump rotation alternatives, as proposed by the Biennium Plan (Scenarios A and B), during the duration of the yellow rule, which lasted for the entire month of July. It was assumed that water users in each critical stretch were submitted to a collective granting process and that the flow to be respected corresponds to the environmental flow. Thus, the objective was to evaluate the remaining flow after the adoption of the pump rotation rules and compare it with the established environmental flow limits.

Table 2. Soil variables used in the calibration of the WEAP model.

Parameters	Description	Units	Default Values
Crop Coeficient	Relative to the reference crop.	-	1
Soil Water Capacity	Effective water holding capacity of upper soil layer.	mm	1000
Deep Water Capacity	Effective water holding capacity of lower, deep soil layer.	mm	1000
Runoff Resistance Factor	Used to control surface runoff response.	-	2
Root Zone Conductivity	Root zone conductivity rate at full saturation.	mm/day	20
Deep Conductivity	Conductivity rate of deep layer at full saturation.	mm/day	20
Preferred Flow Direction	Used to partition the flow out of the root zone layer between interflow and flow to the lower soil layer.	-	0.15
Initial Z1	Initial value for Z1 at the beginning of simulation.	%	30
Initial Z2	Initial value for Z2 at the beginning of simulation	%	30

Table 3. Performance Assessment Criteria for NSE, R^2 and PBIAS statistics recommended by Moriasi et al. (2015) for watershed scale models.

Performance Rating	NSE	R^2	PBIAS
Very Good	$0.8 < NSE \leq 1.00$	$0.85 < R^2 \leq 1.00$	PBIAS < ± 5
Good	$0.7 < NSE \leq 0.8$	$0.75 < R^2 \leq 0.85$	± 5 ≤ PBIAS < ± 10
Satisfactory	$0.5 < NSE \leq 0.7$	$0.60 < R^2 \leq 0.75$	±10 ≤ PBIAS ≤ ± 15
Unsatisfactory	$NSE \leq 0.5$	$R^2 < 0.60$	PBIAS ≥ ± 15

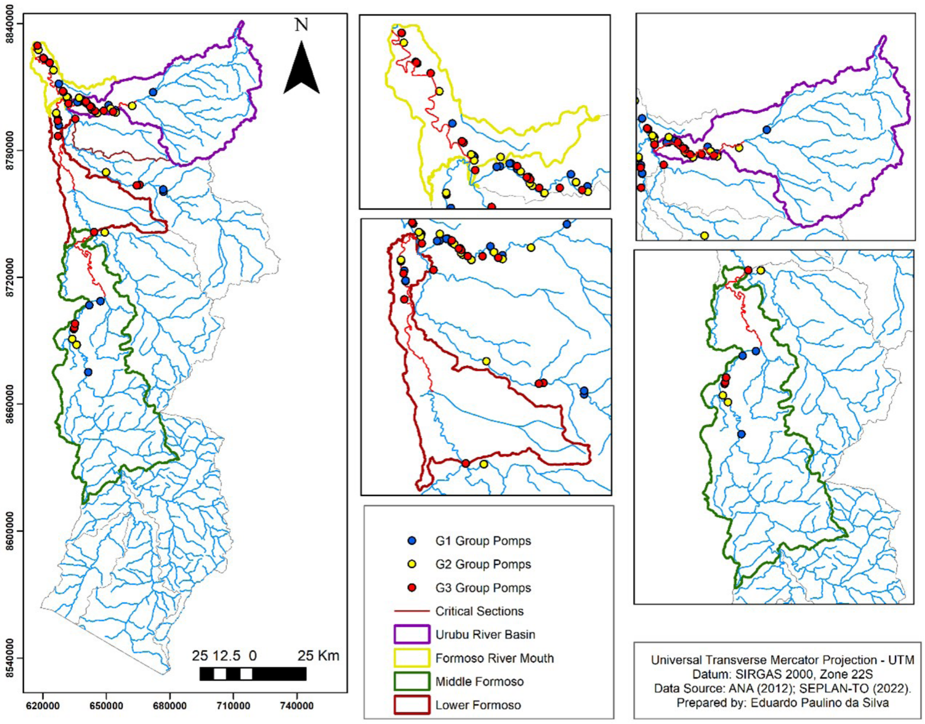

Figure 5. Critical regions in terms of flow and catchment number in the FRB.

According to the IAC (Instituto de Atenção às Cidades, 2017a), in the FRB, four critical sections can be distinguished in terms of the flow and number of intakes, as shown in Figure 5. They are:

- The mouth of the Formoso River: formed by the Formoso River in the stretch between the mouth of the Urubu River and the mouth of the Formoso River itself;
- Lower Formoso: comprises the 24.6 km stretch of the Formoso river upstream, from the mouth of the Urubu river;
- Middle Formsoso: region where the Formoso River Irrigation District (DIRF) is located, on the middle Formoso River, and is 60 km in length;

- Mouth of the Urubu River: the final section of the Urubu River, a tributary of the Formoso River, 25.5 km long and concentrates a large number of abstractions.

Although there were four critical stretches, there was a greater concentration of bombs in the extreme north of the basin, particularly at the mouth of the Urubu River. Upstream in the Lower Formoso sub-basin, the pumps are concentrated in the final stretch of the river just before the inflow of the Urubu River. In the Middle Formoso sub-basin, the concentration of pumps was much lower; however, as highlighted by the IAC (Instituto de Atenção às Cidades, 2017a), because of the DIRF, the volumes collected were high.

Environmental flows were determined from the seasonal Q90 and monthly Q95 reference flows. According to the decree of the State of Tocantins No. 2.342, from 2005, the reference flow used for the definition of permits for surface abstraction in rivers in the state without dams was Q90. This decree determines that the sum of the run-of-river flows to be granted must not exceed 75% of the Q90. Thus, the environmental flow corresponds, at least, to the complement of this portion, that is, 25% of Q90.

However, according to ANA (Agência Nacional de Águas, 2013), regions with seasonality in natural flows should consider the use of monthly reference flows, as these reflect this characteristic, allowing greater demand in the wettest months and greater restriction in the driest months. Whenever possible, the agency adopted a monthly Q95.

In a study carried out by Vergara et al. (2013) at the FRB, the monthly, bimonthly, and quarterly Q90 reference flows were compared with the seasonal Q90 (dry and rainy seasons) provided by the environmental agency of Tocantins. It was found that the monthly Q90 is more appropriate because it presents the intrinsic characteristics of each month, offers more security to environmental agencies, and measures the available flow more accurately. However, because of the scarcity of water in the basin experienced during the dry season, it was decided, for analysis purposes, to simulate the scenarios considering two reference flows: a more flexible one, the seasonal Q90, and a more conservative one, the Q95 monthly.

Thus, the environmental flow (Q env.) in each critical stretch was determined by calculating the portion corresponding to 25% of the selected reference flow. The seasonal Q90 reference flow was obtained from the IAC (Instituto de Atenção às Cidades, 2017b) and the monthly Q95 reference flow from the ANA (Agência Nacional de Águas e Saneamento Básico, 2021). Tables 4 and 5 list these values, respectively.

Reference Scenario

The Reference Scenario represented the basic definition of the FRB model in the WEAP system during the analysis period. This means that this scenario reproduces, as accurately as possible, the real conditions of the FRB for the modeling period of the study, from July 2018 to June 2021,

Table 4. Seasonal Reference Flows (Q90) and Environmental Flows (Qenv.) for the critical sections of the FRB.

Seasonal Reference Flow – Q90 (m^3/s)				
Critical Reagions	**Dry Season**		**Rainy Season**	
	Q90	**Q env.**	**Q90**	**Q90 env.**
Urubu River Mouth	1.25	0.311	28.63	7.16
Upper Formoso	0.68	0.169	15.57	3.89
Middle Formoso	2.07	0.518	47.62	11.91
Lower Formoso	2.94	0.734	67.53	16.88
Formoso River Mouth	4.22	1.055	97.02	24.26

Table 5. Monthly Reference Flows (Q95) and Environmental Flows (Qenv.) for the critical sections of the FRB.

Monthly Reference Flow – Q95 (m^3/s)								
Month	**Formoso River Mouth**		**Lower Formoso**		**Middle Formoso**		**Urubu River Mouth**	
	Q95	**Qenv.**	**Q95**	**Qenv.**	**Q95**	**Qenv.**	**Q95**	**Qenv.**
January	99.1	24.8	65.1	16.3	43.9	10.9	13.72	3.4
Febuary	164.3	41.1	118.5	29.6	89.9	22.5	18.51	4.6
March	273.9	68.5	185.9	46.5	130.8	32.7	35.58	8.9
April	487.4	121.9	276.2	69.1	144.2	36.1	85.35	21.3
May	201.9	50.5	109.3	27.3	51.4	12.8	37.5	9.4
June	57.8	14.4	32.2	8.1	16.2	4.1	10.3	2.6
July	21.7	5.4	12.9	3.2	7.3	1.8	3.6	0.9
August	6.6	1.7	3.6	0.9	1.7	0.4	1.2	0.3
September	2.4	0.6	1.7	0.4	1.2	0.3	0.3	0.1
October	3.9	0.9	3.9	0.9	3.9	0.9	0.01	0.004
November	5.2	1.3	5.1	1.3	5.04	1.3	0.04	0.01
December	18.3	4.5	15.3	3.8	13.4	3.4	1.2	0.3

considering the available input data and calibration quality. From the Reference Scenario, it was possible to build affiliated scenarios that inherit their basic characteristics but will produce different results of water availability according to alternative assumptions based on different water resource management rules adopted in each one of them.

PB-A scenario

Scenario PB-A reproduced the pump operating rules established by Scenario A of the 2018–2019 Biennium Plan and evaluated the remaining flow results. According to IAC (Instituto de Atenção às Cidades, 2018), in this scenario, each group of pumps operated for 40 h, 24 h on the first day, and 16 h on the second day. The pump was turned off for the remaining 8 hours on the second day. Table 6 presents the one-week rotation cycle for Group 1 of the pumps, in addition to the duration of operation and rest for the other groups. Over this period, the total uptake and rest of Group 1 were 64 and 104 h, respectively.

The GAN online application stored daily data on the collected volume, average flow, and pump operating time for each FRB pump. Thus, it was assumed that the pumps of each group were captured during their shift according to the operating time recorded by the application for each group. The results for the remaining flow in the critical sections were compared with the minimum environmental flows corresponding to 25% of seasonal Q90 and 25% of monthly Q95.

PB-B scenario

The PB-B Scenario simulated the Biennium Plan Scenario B during the yellow rule period. According to IAC (Instituto de Atenção às Cidades, 2018), in Scenario B, each group operates for 48 hours without rest between them, suspending all collections on the last day of the week for an uninterrupted 24-hour rest period. In this way, each group operate only once a week, with 48 h of capture and a wait of 120 h per week. Table 7 presents the rotation cycle with the duration of operation for each group and the rest for Scenario B of the Biennium Plan.

As in Scenario PB-A, the pumps during their shifts were captured according to the operating time recorded by the GAN application. The remaining flow results were compared with established environmental flows.

According to the IAC (Instituto de Atenção às Cidades, 2018), the two alternatives for operating the catchment groups in the basin (Tables 6 and 7) are justified based on the uncertainty associated with factors such as: the available flow of watercourses, the water discharge curve of the dams, the volumes stored in the watercourse channels and dams, the soil water conductivity, the magnitude of the recharge water flow from the watercourses, the real water demand of the properties, the water efficiency of the water supply projects irrigation and minimum water levels (level) so that there is no risk of cutting the water flow along the watercourses, because of known sediment banks after the dams.

RESULTS AND DISCUSSIONS

Sensitivity analysis

The results of the Sensitivity Index (SI) for the soil parameters of the FRB model in WEAP are presented in Table 8. These indices were obtained by varying the soil parameters and observing the flow results modeled at the Projeto Rio Formoso fluviometric station (code: 26730000). According to Equation 3, which determines the SI, which is presented in subsection 2.6, I1 and I2 represent the smallest and largest input value for a given parameter, respectively; I12 is the average of these input values; O1 and O2 are the model results for the smallest and largest input values, respectively; and O12 indicates the average of O1 and O2.

The SI values, indicated in Table 8, show that the model results are strongly influenced by the Root Zone Conductivity (RZC), followed by the Runoff Resistance Factor (RRF), Soil Water Capacity (SWC), Deep Water Capacity (DWC), Initial Z1, Initial Z2, and Preferential Flow Direction (PFD). Figure 6 presents a graph of the sensitivity of the model to soil parameters.

As described by Silva et al. (2009), the higher the SI value, the more sensitive the model is to parameter. However, the sign of the index indicates the relationship between the input value of the variable and the result obtained; negative values indicate

Table 6. PB-A Scenario - Rotation cycle with duration of operation for each Group and Rest.

Sequence	Group 1			Group 2			Group 3			Group 1
Week	Sun	Mon		Tue	Wed		Thu	Fri		Sat
Day	1	2		3	4		5	6		7
Operation	✓	✓	Rest	✓	✓	Rest	✓	✓	Rest	✓
Time (h)	24	16	8	24	16	8	24	16	8	24

Table 7. PB-B Scenario - Rotation cycle with duration of operation for each Group and Rest.

Sequence	Group 1		Group 2		Group 3		All Groups
Week	Sun	Mon	Tue	Wed	Thu	Fri	Sat
Day	1	2	3	4	5	6	7
Operation	✓	✓	✓	✓	✓	✓	Rest
Time (h)	24	24	24	24	24	24	24

Table 8. Sensitivity analysis of the WEAP model for the FRB.

Parameters	Default	I1	I2	I12	O1	O2	O12	SI	Rating
SWC	1000	100	1900	1000	159.9	92.4	126.2	-0.297	3
DWC	1000	100	1900	1000	105.7	113.1	109.4	0.038	5
RRF	2	0.2	3.8	2	182.6	101.3	141.9	-0.318	2
RZC	20	2	38	20	42.3	147.2	94.8	0.615	1
DC	20	2	38	20	95.8	107.2	101.5	0.063	4
PFD	0.15	0.015	0.285	0.15	108.1	108.1	108.1	0.000	8
Initial Z1	30	3	57	30	108.0	108.4	108.2	0.002	7
Initial Z2	30	3	57	30	105.7	108.8	107.3	0.016	6

Table 9. Result and evaluation of the performance statistics for the calibration of the flow modeled in the Projeto Rio Formoso Station.

Performance Statistics	Projeto Rio Formoso Station	Performance Classification	
NSE	0.89	$0.8 < NSE \leq 1.00$	Very Good
PBIAS (%)	2.7	$PBIAS < \pm 5$	Very Good
R^2	0.89	$0.85 < R^2 \leq 1.00$	Very Good

an inversely proportional relationship, whereas positive values indicate a directly proportional relationship.

In descending order, the soil parameters that interfered the most with the modeled average discharge results were the RZC, RRF, and SWC. Among these, only RZC showed a directly proportional relationship with the results. Thus, the higher the value, the higher the average flow. However, RRF and SWC are inversely proportional to the results; therefore, the higher their values, the lower the modeled flows. The remaining parameters had very low SI values and little influence on the model.

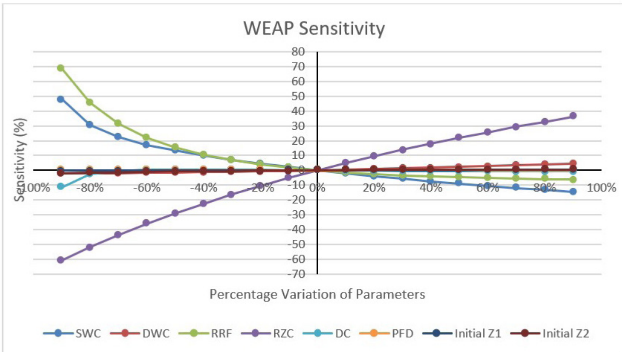

Figure 6. WEAP sensitivity to calibration parameters

Calibration results

Calibration of the WEAP model for FRB was carried out considering the daily historical series of flow from the Foz Rio Urubu, Projeto Rio Formoso, and Foz Rio Formoso stations, submitted to gap filling through the application of Multiple Linear Regression and Regionalization of Flows.

The calibration was conducted from upstream to downstream because the values obtained with the performance statistics in the sections closest to the outlet were influenced by the adjustments made in the more distant sections. Thus, calibration was first carried out first at the Projeto Rio Formoso station, later at the Foz Rio Urubu station, and finally at the Foz Rio Formoso station. Figure 7 presents a hydrograph of the modeled discharge (red) and observed discharge (black) for the Projeto Rio Formoso station, and Table 9 presents the respective NSE, PBIAS, and R^2 values.

The calibration at the Projeto Rio Formoso station showed NSE, PBIAS and R^2 values of 0.89, 2.7%, and 0.89, respectively. As shown in Table 9, the three performance statistics were classified as very good, indicating that the model represents the data observed at the Projeto Rio Formoso Station very well. Adjustment of the flows modeled at this station was carried out by modifying the soil parameters of the sub-basins located upstream, namely Piaus, Pau Seco, Upper Formoso, and Middle Formoso. Table 10 presents the final values of the soil parameters for these sub-basins after the calibration process at the Projeto Rio Formoso station

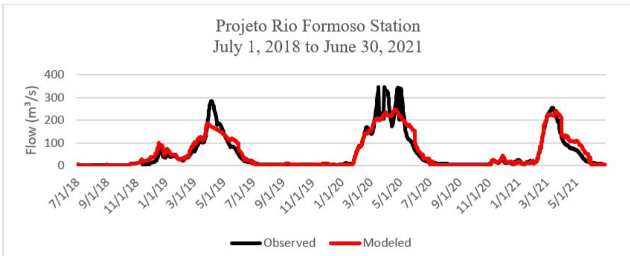

Figure 7. Observed flow and simulated flow at Projeto Rio Formoso Station.

After calibrating the results at the Projeto Rio Formoso station, an adjustment was made at the Foz Rio Urubu station by modifying the soil parameters of the upstream Dueré, Ribeirão Lago Verde, and Urubu subbasins. Figure 8 presents a hydrograph of the observed and modeled flows for this station. Table 11 shows the respective values obtained using the performance statistics.

As shown in Table 11, the results of the performance statistics for the calibration of the Foz Rio Urubu station presented a lower classification than that achieved in the calibration of the

Table 10. Final values of the calibration parameters after adjusting the modeled flow to the observed flow at the Projeto Rio Formoso Station.

VARIABLES		SUB-BASINS				
		Units	Piaus	Pau Seco	Upper Formoso	Middle Formoso
SWC		mm	5500	5500	5500	7500
DWC		mm	9000	9000	9000	7000
RRF						
	Farming	-	20	20	20	20
	Non Vegetated Area	-	10	10	10	10
	Irrigated Agriculture	-	-	-	-	30
	Water	-	10	10	10	10
	Forest	-	20	20	20	20
	Non Forest Naturation Formation	-	20	20	20	20
RZC		mm/day	105	105	100	10
DC		mm/day	3	3	3	2
PFD						
	January	-	0.9	0.9	0.9	0.9
	Febuary	-	1	1	1	1
	March	-	1	1	1	1
	April	-	1	1	1	1
	May	-	0.85	0.85	0.85	0.85
	June	-	0.7	0.7	0.7	0.7
	July	-	0.3	0.3	0.3	0.3
	August	-	0	0	0	0
	September	-	0.2	0.2	0.2	0.2
	October	-	0.1	0.1	0.1	0.1
	November	-	0.4	0.4	0.4	0.4
	December	-	0.7	0.7	0.7	0.7
Initial Z1		%	0	0	0	0.1
Initial Z2		%	0	0	0	0

Table 11. Result and evaluation of the performance statistics for the calibration of the flow modeled in the Foz Rio Urubu Station.

Performance Statistics	Foz do Rio Urubu Station	Performance Classification	
NSE	0.79	$0.7 < NSE \leq 0.8$	Good
PBIAS (%)	6.7	$\pm 5 \leq PBIAS < \pm 10$	Good
R^2	0.8	$0.75 < R^2 \leq 0.85$	Good

Projeto Rio Formoso station; however, they were still considered good. NSE = 0.79, PBIAS = 6.7, $R^2 = 0.8$. The final values of the soil parameters for the Dueré, Ribeirão Lago Verde, and Urubu subbasins are presented in Table 12.

Finally, the model was calibrated at the Foz Rio Formoso station, close to the FRB outlet, modifying the soil parameters of the Xavante and Lower Formoso subbasins. The hydrographs of the observed and simulated flows for that station are presented in Figure 9, and the results of the performance statistics are listed in Table 13.

According to Table 13, the performance statistics for the Foz Rio Formoso station were NSE = 0.89, PBIAS = -7.4%, and $R^2 = 0.91$. The performance classifications for NSE and R^2 were very good, whereas the PBIAS obtained a good fit. In addition, PBIAS presented a negative value, unlike the other stations, which indicated an average overestimation bias in the model. The final values of the soil parameters for the Xavante and Lower Formoso subbasins are listed in Table 14.

Scenario analysis

Formoso Irrigation District

Figure 10 presents the results of the remaining flow in the final stretch of the Medium Formoso in the DIRF region for the Reference, PB-A, and PB-B scenarios over the month of July 2020, as well as the flow limits established by the collective granting of the stretch, corresponding to 25% of the seasonal Q90 (0.52 m3/s) and 25% of the monthly Q95 (1.83 m3/s), respectively. The average, minimum, and maximum remaining flow values as well as the percentage of days with daily flow values above the environmental flow limits are listed in Table 15 for each scenario.

As shown in Figure 10, during the first half of July, the daily flow for the three scenarios was considerably higher than the environmental flow limits established for the stretch. However, as

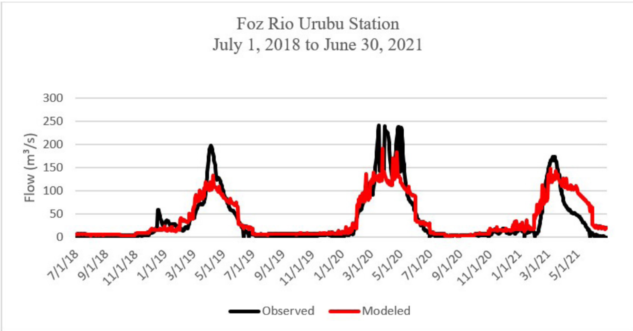

Figure 8. Observed flow and simulated flow at Foz Rio Urubu Station.

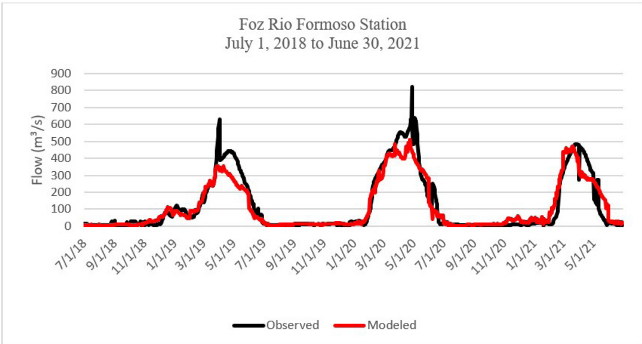

Figure 9. Observed flow and simulated flow at Foz Formoso Station.

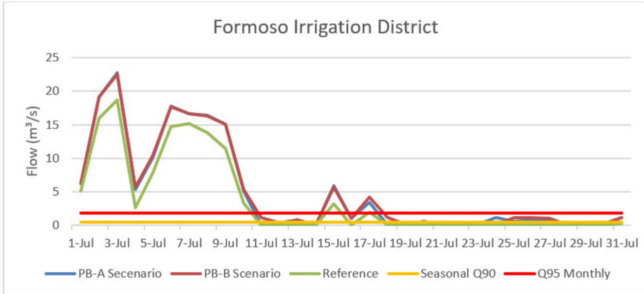

Figure 10. Remaining flow in the critical section of the DIRF for the Reference scenarios, PB-A and PB-B, during the month of July 2020.

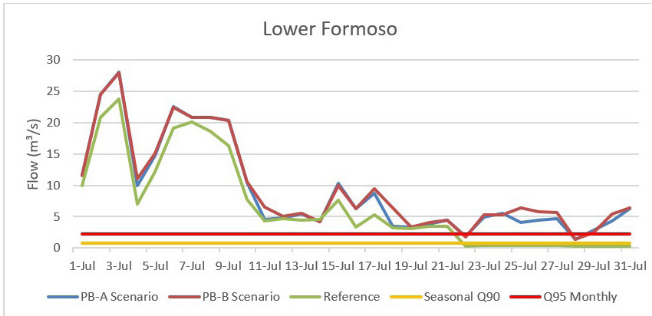

Figure 11. Remaining flow in the critical Lower Formoso section for the Reference scenarios, PB-A and PB-B, during the month of July 2020.

of July 11, this flow declined considerably and oscillated within these limits. The low flow from the second quarter of the month may indicate the anticipation of the critical period scheduled for August 1st.

According to Table 15, the Reference Scenario showed an average monthly flow of 3.69 m^3/s and minimum and maximum flows of 0.003m^3/s and 18.68 m^3/s, respectively. In 38% of the days the flow was more than 25% of the seasonal Q90, which also represented the number of days which flows of more than 75% of the monthly Q95.

With the application of the rules of the PB-A scenario, the average monthly flow rate increased by 32% and reached a value of 4.87 m^3/s, while the minimum and maximum flow rates were equal to 0.027 m^3/s and 22.74 m^3/s, respectively. In addition, for 61% of the days, the flows were above 25% of the seasonal Q90, representing an increase of 23% from the Reference Scenario, with no increase in the number of days with flows exceeding 25%. of the monthly Q95.

In the PB-B scenario the average monthly flow rate was 5 m^3/s, which corresponds to an increase of 36% compared with the reference scenario. The minimum and maximum flows were 0.032 and 22.52 m^3/s, respectively. With the rotation of the pumps, the fraction of days with flows were greater than 25% of the seasonal Q90 increased by 23%, reaching 61% of the days, whereas the fraction of days with flows greater than 25% of Q95 was maintained.

Over the course of the month, the flow curves of the PB-A and PB–B scenarios showed quite similar behavior. Both scenarios obtained the same number of days with flows above the flexible and conservative environmental flow limits, as listed in Table 15. However, the PB-B scenario was found to be the best in terms of guaranteeing water safety, as its average monthly flow was slightly higher than that of the BP-A scenario.

Lower Formoso

Figure 11 presents the flow results in the final section of Lower Formoso for the Reference scenarios, PB-A and PB-B, throughout the month of July 2020, as well as the environmental flow limits established by the collective granting of the section, corresponding to 25% of the seasonal Q90 (0.73 m^3/s) and 25% of the monthly Q95 (2.22 m^3/s). Average (Q ave.), and minimum (Q min.), and maximum flow (Q max) values, as well as the number of days with daily flow values higher than the environmental flow limits, are listed in Table 16.

In Lower Formoso, the flow in the Reference Scenario was above the environmental flow limits for almost the entire month. However, from the 23rd, the flow was zero until the end of the period, even after the influx of the Xavante River at the height of the section. In the Reference Scenario, the average flow was 6.55 m^3/s and the maximum flow was 23.82 m^3/s. In 68% of the days, the flow exceeded both the flexible limits and the environmental flow preservative.

As shown in Table 16, the application of the rotation rules to the water collector pumps, envisaged in the PB-A scenario,

Table 12. Final values of the calibration parameters after adjusting the modeled flow to the observed flow at the Foz Rio Urubu Station.

VARIABLES		Units	SUB-BASINS		
			Dueré	Rib. Lago Verde	Urubu
SWC		mm	6700	2500	3400
DWC		mm	6500	5500	6500
RRF					
	Farming	-	20	20	20
	Non Vegetated Area	-	10	10	10
	Irrigated Agriculture	-	30	30	30
	Water	-	10	10	10
	Forest	-	20	20	20
	Non Forest Naturation Formation	-	20	20	20
RZC		mm/day	20	30	45
DC		mm/day	3	3	2
PFD					
	January	-	0.9	0.9	0.9
	Febuary	-	1	1	1
	March	-	1	1	1
	April	-	1	1	1
	May	-	0.85	0.85	0.85
	June	-	0.7	0.7	0.7
	July	-	0.3	0.3	0.3
	August	-	0	0	0
	September	-	0.2	0.2	0.2
	October	-	0.1	0.1	0.1
	November	-	0.4	0.4	0.4
	December	-	0.7	0.7	0.7
Initial Z1		%	0.1	0.1	0.1
Initial Z2		%	0	0	0

Table 13. Result and evaluation of the performance statistics for the calibration of the flow modeled in the Foz Rio Formoso Station.

Performance Statistics	Foz do Rio Formoso	Performance Classification	
NSE	0.89	0.8 < NSE ≤ 1.00	Very Good
PBIAS (%)	-7.4	± 5 ≤ PBIAS < ± 10	Good
R^2	0.91	0.85 < R^2 ≤ 1.00	Very Good

increased the average monthly flow of the Reference Scenario by 39%. This value corresponds to 9.1 m^3/s. The minimum and maximum flows obtained for the period were equal to 0.93 m^3/s and 28.11 m^3/s, respectively. In addition, in 100% of the days the flow was more than 25% of the seasonal Q90, whereas the proportion of days with values greater than the environmental flow, referring to 25% of the monthly Q95, corresponded to 94%.

With the operating rules of the pumps in the PB-B scenario, the average flow rate becomes 9.5 m^3/s, corresponding to a 44% increase in the average monthly flow rate in the Reference Scenario. The recorded minimum and maximum flows correspond to 0.93 m^3/s and 27.9 m^3/s, respectively. As in the PB-A scenario, in 100% of the days the flow exceeded the environmental flow, referring to 25% of the seasonal Q90, and in 93%, it exceeded 25% of the monthly Q95.

As in the Formoso Irrigation District, in the critical section of the Lower Formoso the flow curves corresponding to scenarios PB-A and PB-B were similar. The application of the rotation in the two scenarios, added to the influx of the Xavante River, promoted an increase in the remaining flow to values above the conservative limit, especially from the second half, except for the flow on days 22 and 28, which was slightly below this limit.

Even if the average monthly flow of the PB-B scenario is higher than that of the BP-A scenario, as indicated in Table 16, the percentage of days in this scenario that exceeded the limit corresponding to 25% of the monthly Q95 was slightly higher than the one and therefore met the minimum flow requirements most of the time, representing the best scenario for this critical stretch.

Mouth of the Urubu River

Figure 12 shows the flow results at the mouth of the Urubu River for the Reference, PB-A, and PB-B scenarios throughout July 2020, as well as the minimum environmental flow limits established by the collective grant for the stretch, corresponding to the seasonal Q90 (0.311 m^3/s) and the monthly Q95 (0.90 m^3/s). Average (Q ave.), and minimum (Q min.), and maximum flow (Q

Table 14. Final values of the calibration parameters after adjusting the modeled flow to the observed flow at the Foz Rio Formoso Station.

VARIABLES		Units	SUB-BASINS	
			Xavante	Lower Formoso
SWC		mm	3000	7500
DWC		mm	2500	7000
RRF				
	Farming	-	20	20
	Non Vegetated Area	-	10	10
	Irrigated Agriculture	-	30	30
	Water	-	10	10
	Forest	-	20	20
	Non Forest Naturation Formation	-	20	20
RZC		mm/day	40	35
DC		mm/day	3	2
PFD				
	January	-	0.9	0.9
	Febuary	-	1	1
	March	-	1	1
	April	-	1	1
	May	-	0.85	0.85
	June	-	0.7	0.7
	July	-	0.3	0.3
	August	-	0	0
	September	-	0.2	0.2
	October	-	0.1	0.1
	November	-	0.4	0.4
	December	-	0.7	0.7
Initial Z1		%	0.1	0.1
Initial Z2		%	0	0

Table 15. Average, minimum and maximum flow values and portion of days with daily flow exceeding the environmental flow limits corresponding to the critical section of the Formoso District River.

Formoso Irrigation District					
Scenarios	Q ave.	Q min.	Qmax	% days with Q day greater than 25% of seasonal Q90 (0.52 m^3/s)	% days with Q day greater than 25% of monthly Q95 (1.83 m^3/s)
Reference	3.69	0.003	18.68	38	38
PB-A	4.87	0.027	22.74	61	38
PB-B	5	0.032	22.52	61	38

Table 16. Average, minimum and maximum flow values and portion of days with daily flow exceeding the environmental flow limits corresponding to the Lower Formoso critical section.

Lower Formoso					
Scenários	Q ave.	Q min.	Qmax	% days with Q day greater than 25% of seasonal Q90 (0.73 m^3/s)	% days with Q day greater than 25% of monthly Q95 (2.22 m^3/s)
Reference	6.55	null	23.82	68	68
PB-A	9.1	0.93	28.11	100	94
PB-B	9.5	0.93	27.9	100	93

max) values, as well as the number of days with daily flow values higher than the environmental flow limits, are listed in Table 17.

According to IAC (Instituto de Atenção às Cidades, 2018), the Urubu River Mouth is the critical section with the highest number of absorption pumps per river extension. This is reflected in the remaining flow in the region. As shown in Table 17, the Reference Scenario showed an average flow rate of 0.21 m^3/s and the maximum flow rate reached 1.80 m^3/s. In 16% of the days, the flows exceeded the environmental flow corresponding to the flexible limit, while only on the 6th and 7th days they exceed the conservative limit

Table 17. Values of average, minimum and maximum flow and portion of days with daily flow higher than the environmental flow limits corresponding to the critical section Mouth of Urubu River.

Mouth of the Urubu River					
Scenarios	**Q ave.**	**Q min.**	**Q max.**	**% days with Q day greater than 25% of seasonal Q90 (0.311 m³/s)**	**% days with Q day greater than 25% of monthly Q95 (0.90 m³/s)**
Reference	0.21	null	1.80	16	6
PB-A	0.88	0.02	2.4	61	45
PB-B	1.07	null	2.5	61	58

Table 18. Values of average, minimum and maximum flow and portion of days with daily flow higher than the environmental flow limits corresponding to the critical section Mouth of Formoso River.

Mouth of the Formoso River					
Scenários	**Q ave.**	**Q min.**	**Qmax**	**% days with Q day greater than 25% of seasonal Q90 (1.05 m³/s)**	**% days with Q day greater than 25% of monthly Q95 (5.43 m³/s)**
Reference	8.64	0.06	26.36	81	48
PB-A	16.1	6.11	35.01	100	100
PB-B	17.2	7.5	36.1	100	100

With the application of the rotation rules proposed by the PB-A scenario, the average flow increased by 0.67 m^3/s and reached the value of 0.88 m^3/s. In this scenario, the minimum and maximum flows were equal to 0.02 m^3/s and 2.4 m^3/s, respectively. In 61% of the days, the daily flow exceeded the limit corresponding to 25% of the seasonal Q90, and in 45% of the days, the flow corresponded to 25% of the monthly Q95.

In the PB-B scenario, the average flow rate was 1.07 m^3/s, which represented an increase of 0.86 m^3/s in the mean flow rate for the reference scenario. In 61% of the days, the daily flow exceeded the limit corresponding to 25% of the seasonal Q90, whereas in 58% of the days, the flow was greater than 25% of the monthly Q95.

From the information presented in Table 17, it was found that the rotation proposed by the PB-B scenario would be the best alternative to the critical stretch of the Mouth of the Urubu River, to the detriment of the PB–A scenario, because its average monthly flow was approximately 21.5% higher, and the share of days in which the flow exceeded the conservative limit of environmental flow was 13% higher.

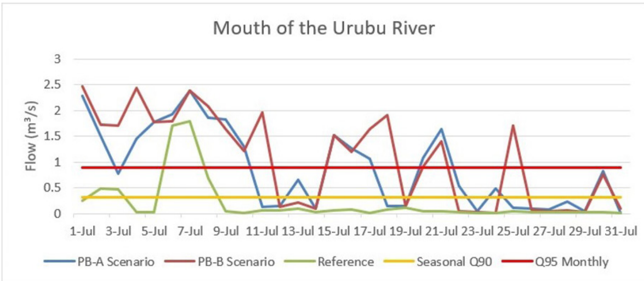

Figure 12. Remaining flow in the critical Urubu River section for the Reference scenarios, PB-A and PB-B, during the month of July 2020.

Mouth of the Formoso River

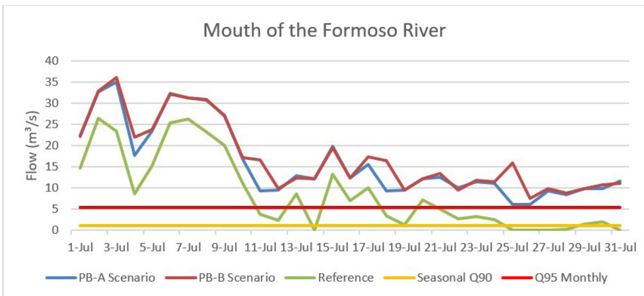

Figure 13. Remaining flow in the critical Rio Formoso mouth section for the Reference scenarios, PB-A and PB-B, during the month of July 2020.

Figure 13 presents the results of the flow at the mouth of the Formoso River for the Reference, PB-A, and PB-B scenarios throughout the month of July 2020, as well as the minimum environmental flow limits established by the collective granting of the stretch, corresponding to 25% of the seasonal Q90 (1.05 m^3/s) and 25% of the monthly Q95 (5.43 m^3/s). Average (Q ave.), and minimum (Q min.), and maximum flow (Q max.) values, as well as the number of days with daily flow values higher than the environmental flow limits, are listed in Table 18.

With the influx of the Xavante and Urubu Rivers, the flow in the foothills of the Formoso River in the reference scenario was below the limits of environmental flow in only a few days. In this scenario, the average monthly flow rate was 8.64 m^3/s, and the minimum and maximum flow rates were 0.06 m^3/s and 26.36 m^3/s respectively. In 81% of the days, the flow rate was higher than 25% of the seasonal Q90, whereas the share of days with flow values greater than 75% of the monthly Q95 was equal to 48%.

In the scenario PB-A, the application of the pump rotation increased by 86% the average monthly flow of the stretch, reaching 16.1 m^3/s. The minimum and maximum flows were equal to

6.11 m^3/s and 35.01 m^3/s, respectively. Throughout the month, the daily flow exceeded the environmental flow limits.

In the PB-B scenario, the monthly average was 17.2 m^3/s, twice the value calculated in the reference scenario. The minimum and maximum flow rates were 7.5 m^3/s and 36.1 m^3/s, respectively. Similar to the PB-B scenario, the daily flow exceeded the environmental flow limits during the month.

The rotation rules applied to the Formoso River foam pumps maintained the daily values of the remaining flow above the minimum environmental flow limit throughout July. This behavior can also be attributed to the rotation implemented in critical sections located upwards, as they contribute to greater water availability for downstream users. The PB-B scenario stood out as the best because it presented a higher average monthly flow than the PB-A scenario.

DISCUSSIONS

This research aimed to carry out a hydrological simulation of the FRB using the WEAP tool and model in regions of conflict over water use scenarios based on the rotation rules for surface water capture pumps recommended by the 2018 – 2019 Biennium Plan. The influence of such rules was analyzed on the remaining flow of water bodies in these regions, considering the context of collective granting, in which minimum environmental flows, determined based on the reference flows Q90 seasonal (flexible limit) and Q95 monthly (conservative limit) must be preserved downstream of the critical stretches.

The FRB hydrological model in WEAP was calibrated using daily flow data recorded by river stations, considering the period beginning in July 2018 and extending to June 2021. Three stations were selected, whose statistics obtained, were rated as "very good", according to the evaluation criterion proposed by Moriasi et al. (2015). They were: Projeto Rio Formoso (NSE = 0.89, PBIAS = 2.7, R^2 = 0.89), Foz Rio Urubu (NSE = 0.79, PBIAS = 6.7, R^2 = 0.8), and Foz Río Formoso (NSE= 0.89, PBIAS = -7.4, R^2= 0.91).

The modeling of the PB-A and B-B scenarios, which reproduced the rotating rules of the absorption pumps proposed by the Biennium Plan during July, indicated, in almost all critical sections, an increase in the remaining flow above the flexible (25% of the seasonal Q90) and conservative (25% of the monthly Q95) limits of the environmental flow, suggesting that the implementation of these measures would bring benefits to users. In the past, the environmental body has stopped implementing the guidelines of the plan due to the resistance of users, who disagreed with the dates and periods set for the rotation.

In general, the PB-B scenario was slightly better at meeting the environmental flow requirements than the PB-A scenario. Over the course of a week, the total operating hours of the pumps was 144 h, and the interval was 24 h for both scenarios. However, in the PB-A scenario, the interval occurred during the week and was fragmented, whereas in the PB-B scenario, the interval was throughout the entire Saturday, indicating that 144 h of pump operation in the PB-A scenario captured a volume of water slightly higher than the volume captured by the PB-B scenario.

The critical stretch of the mouth the Formoso River produced the best results for the remaining flow for the PB-A and PB - B scenarios because, in addition to benefiting from the rules applied in the region itself, it was favored by those implemented in the stretches located upwards. For both scenarios, the daily remaining flow was above the conservative environmental flow limit throughout July; however, the PB-B scenario obtained a higher average monthly flow.

The mouth of the Urubu River presented the most severe picture. With the highest number of pumps per river extension, the average monthly flow rate obtained for the PB-A and B-B scenarios did not reach 1.1 m^3/s. There is a consensus among the researchers and technicians working at the FRB that the Urubu River is intermittent, although this claim is more empirical than scientific. The PB-B scenario better met the environmental flow requirements, with 58% of the days with daily flow above the conservative limit, compared to 45% of the PB–A scenario.

In Medium Formoso, the remaining flows in the second quarter of the month were considerably lower than those recorded in the first quarter, and the same behavior was observed in the Formso Irrigation District section. However, in contrast, the rotation rules implemented by scenarios PB-A and PB-B, added to the influx of the Xavante River, increased by more than 90% of the days with flow above the conservative limit of environmental flow. With a slight difference between the scenarios in each section, in the Medium Formoso, scenario PB-A obtained better performance, whereas in the Formoso Irrigation District, it was the PB-B scenario.

This article focuses on the assessment of FRB's water safety in the face of the implementation of the Guidelines of the Biennium Plan in critical sections. In this way, the impacts, especially economic ones, on users were not assessed. However, as IAC (Instituto de Atenção às Cidades, 2018) points out, the proposals for the rotation of the Biennium Plan were based on previous experiences of the environmental body of Tocantins, which, through the water balance of each section and the participation of users, identified a potential 40-hour bomb journey.

In addition, in recent years, users have used traffic light rules so that, empirically, they do not allow the critical quota to be reached. The period of the yellow rule, in which the rotating rules should be applied, serves as a warning period for farmers to prepare and implement action based on experimental knowledge to avoid collapse. Such actions have enabled producers to reach the end of the irrigation period of their crops. Thus, it is believed that there would be no greater economic impacts, such as crop loss, due to the Biennium Plan.

Finally, the Biennium Plan is part of the GAN solution, which was agreed upon in court between the parties, so that the proposed rules would have to be put into practice, which would probably require adjustments, such as a greater number of rain stations, to ensure that the catches were not linked to distant stations. This could interfere with the results, either by distance or by the large number of catches along the river, in addition to the arrangement of more accurate environmental flow values because the rain stations are new and the historical series are very short.

CONCLUSIONS

In view of the above, it is believed that the Biennium Plan's proposals have the potential to contribute to the management of water resources in the FRB, especially during drought, a period which conflicts over water use intensify. The application of hydrological models as decision support tools, which enable the evaluation of different management scenarios considering the multiple and competing uses of water, results in information that can constantly contribute to improving planning. Sharing this information with users promotes their participation in the decision-making process, strengthening collective management in the basin, and consequently, reducing conflicts over water use.

ACKNOWLEDGEMENTS

This work was supported by the Coordination for the Improvement of Higher Education Personnel - Brazil (CAPES) - project "Research Network for High-Level Management of Water Resources in the Formoso River Basin - TO" funded by the Call CAPES-ANA - Pro-Hydric Resources Call N. 16/2017, and the University of Brasília Foundation (FUB/UnB) through financial support through the notice of the Dean of Graduate Studies (DPG) N. 0011/2022.

REFERENCES

Agência Nacional de Águas e Saneamento Básico – ANA. (2011). *Cadernos de capacitação em recursos hídricos. Outorga de direito de uso de recursos hídricos* (Vol. 6). Retrieved in 2023, September 1, from https://arquivos.ana.gov.br/institucional/sge/CEDOC/Catalogo/2012/OutorgaDeDireitoDeUsoDeRecursosHidricos.pdf

Agência Nacional de Águas e Saneamento Básico – ANA. (2013). *Manual de procedimentos técnicos e administrativos de outorga de direito de uso de recursos hídricos 2013*. Retrieved in 2023, August 25, from http://bibliotecadigital.economia.gov.br/handle/123456789/433

Agência Nacional de Águas e Saneamento Básico - ANA. (2021). *Disponibilidade Hídrica Superficial (BHO 2017 5K)*. Retrieved in 2023, August 25, from https://metadados.snirh.gov.br/geonetwork/srv/api/records/7ac42372-3605-44a4-bae4-4dee7af1a2f8

Alves, K. C. C. D. L. F., Viola, M. R., Souza, P. A., Giongo, M., & Mello, C. R. (2015). Avaliação temporal dos conflitos de uso do solo na bacia hidrográfica do rio Formoso, Tocantins. *Pesquisa Florestal Brasileira*, *35*(83), 271-283. http://dx.doi.org/10.4336/2015.pfb.35.83.820.

Companhia Nacional de Abastecimento - CONAB. (2015). *A cultura do arroz*. CONAB. Retrieved in 2023, August 25, from https://biblioteca.conab.gov.br/phl82/pdf/2015_Cultura_do_arroz.pdf

Fard, M. D., & Sarjoughian, H. S. (2021). A RESTful framework design for componentizing the water evaluation and planning (WEAP) system. *Simulation Modelling Practice and Theory*, *106*, 102199.

Instituto Brasileiro de Geografia e Estatística – IBGE. (2007). *Manual Técnico de Pedologia*. Retrieved in 2023, August 25, from https://www.agrolink.com.br/downloads/manual%20t%C3%A9cnico%20de%20pedologia.pdf

Instituto de Atenção às Cidades – IAC. (2017a). *Relatório Fase B: Resultados Parciais e Recomendações*. Tocantins: Universidade Federal do Tocantins.

Instituto de Atenção às Cidades – IAC. (2017b). *Gestão de Alto Nível*. Universidade Federal do Tocantins [Power Point slides]. Retrieved in 2023, August 25, from https://www.confea.org.br/sites/default/files/antigos/Palmas_FernanVergaraFigueiroa.pdf

Instituto de Atenção às Cidades – IAC. (2018). *Gestão de Alto Nível. Plano do Biênio 2018-2019*. Universidade Federal do Tocantins. Retrieved in 2023, August 25, from https://central.to.gov.br/download/43038

Kirilov, L., & Bournaski, E. (2019). Functionalities of WEAP software to water balance modelling. In *Conference Proceedings "Climate, atmosphere and water resources during climate change"* (pp. 73-79). Bulgaria.

Moriasi, D. N., Gitau, M. W., Pai, N., & Daggupati, P. (2015). Hydrologic and water quality models: performance measures and evaluation criteria. *Transactions of the ASABE*, *58*(6), 1763-1785. http://dx.doi.org/10.13031/trans.58.10715.

Nearing, M. A., Deer-Ascough, L., & Laflen, J. M. (1990). Sensitivity analysis of the WEPP hillslope profile erosion model. *Transactions of the ASAE. American Society of Agricultural Engineers*, *33*(3), 839-840. http://dx.doi.org/10.13031/2013.31409.

Notisso, P. F. (2020). *Aplicação do modelo WEAP na avaliação de alocação de água do reservatório dos Pequenos Libombos, Moçambique* (Dissertação de mestrado). Programa de Pós-Graduação em Ciências Ambientais, Universidade Federal de Goiás, Goiânia. Retrieved in 2023, August 25, from https://repositorio.bc.ufg.br/tede/handle/tede/10365

Opere, A. O., Waswa, R., & Mutua, F. M. (2022). Assessing the impacts of climate change on surface water resources using WEAP model in Narok County, Kenya. *Front Water*, *3,* 789340. https://doi.org/10.3389/frwa.2021.789340.

Reis, P., Fontes, A., & Medeiros, Y. (2020). Definição da vazão de contribuição como estratégia de gestão na bacia hidrográfica do Rio São Francisco. *Revista de Gestão de Água da América Latina*, *17*, e21. http://dx.doi.org/10.21168/rega.v17e21.

Secretaria de Planejamento e Orçamento – SEPLAN. (2017). *Diagnóstico Ecológico Econômico – Meio Natural. Zoneamento Ecológico-Econômico do Estado do Tocantins*. Retrieved in 2023, August 25, from https://central.to.gov.br/download/213390

Secretaria de Recursos Hídricos e Meio Ambiente do Tocantins – SRHMA. (2007). *Plano de Bacia Hidrográfica do Rio Formoso. Relatório Síntese*. Retrieved in 2023, August 25, from https://central3.to.gov.br/arquivo/269430/

Sieber, J. (2006). *WEAP water evaluation and planning system*. Retrieved in 2023, August 25, from https://scholarsarchive.byu.edu/cgi/viewcontent.cgi?article=3544&context=iemssconference

Silva, J. M., Pruski, F. F., Rodrigues, L. N., & Cecílio, R. A. (2009). Modelo para obtenção do hidrograma de escoamento superficial em bacias hidrográficas. 1. Desenvolvimento e análise de sensibilidade. *Agrária*, *4*(1), 78-84. http://dx.doi.org/10.5039/agraria.v4i1a13.

Spolidorio, P. C. M. (2017). A alocação negociada de água como estratégia de regulação responsiva. *Journal of Law and Regulation*, *3*(1), 183-198.

Stockholm Environment Institute - SEI. (2015). "*User Guide". Water Evaluation and Planning System*. Retrieved in 2023, August 25, from https://www.weap21.org/downloads/WEAP_User_Guide.pdf

Stockholm Environment Institute - SEI. (2023). *Why WEAP?* Retrieved in 2023, August 25, from https://www.weap21.org/index.asp?action=201

Teklu, S., Soliman, A. H., & El-Zawahry, A. (2020). Testing the WEAP hydrologic model for awash basin, Ethiopia "Soil Moisture Module with Watershed Demand Approach". *Civil Environ. Res*, *12*, 59-74. http://dx.doi.org/10.7176/CER/12-3-07.

Vergara, F. E., Reis, F. C., Magalhães Filho, L. N. L., & Rezende, C. S. A. (2013). Proposta de vazão de referência Q 90 para o Rio Formoso na Bacia do Araguaia. *Engenharia Ambiental*, *10*(1), 84-102.

Zehtabian, E., Masoudi, R., Yazdandoost, F., Sedghi-Asl, M., & Loáiciga, H. A. (2023). Investigation of water allocation using integrated water resource management approaches in the Zayandehroud River basin, Iran. *Journal of Cleaner Production*, *395*, 136339.

Authors contributions

Eduardo Paulino da Silva: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing.

Conceição de Maria Albuquerque Alves: Metodology, Supervision, Visualization, Writing – review & editing

Nicole John Volken: Methodology.

Fernan Enrique Vergara Figueroa: Methodology, Project administration.

Ricardo Tezini Minoti: Metodology, Supervision, Visualization, Writing – review & editing.

Editor in-Chief: Adilson Pinheiro

Associated Editor: Fábio Veríssimo Gonçalves