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Water rights in sugarcane irrigation: influence of irrigation criteria and probability levels adopted for ET_o and rainfall

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ABSTRACT: Sugarcane irrigation is one of the main technologies to increase productivity and profitability in the sugar-energy sector. However, to improve the management of water resources in Brazil, growers need to obtain a water rights permitfrom regulatory agencies. The calculation of water rights is determined from data based on estimates of rainfall and reference evapotranspiration (ET_o) provided by the Agência Nacional de Águas e Saneamento Básico (ANA). The primary hypothesis of this study was that the method proposed by ANA to calculate water rights did not provide operational security since it lacked an adequate probabilistic character. As a corollary, we included a secondary hypothesis stating that determining flows through the simplified FAO method proposed in the CROPWAT 8.0 manual displayed vulnerability due to the criteria to choose the representative years. This research aimed to compare such methodologies with a more detailed case study (standard method), taking into account the temporal variability of these estimates, the irrigation criteria, and the probability of occurrence of ET_o and rainfall to determine water rights for sugarcane irrigation. During the period between Apr and Sept (dry period), the calculation method proposed by ANA met the needs of the project. However, when rainfall was concentrated (Oct to Mar), the calculation method tended to underestimate the monthly values of available flows. The simplified method proposed by FAO and the alternative method proposed here approached ideal conditions.

Keywords: *Saccharum* spp., reference evapotranspiration, water balance, water use permit

Introduction

Productivity of sugarcane crops depends significantly on the interaction of three main factors: plants, production environment, and management practices. Water deficit is the most severe adverse factor in the production environment. Even in areas with a humid climate, irregular distribution of rainfall in some periods can limit plant growth. Sugarcane crops and mills worldwide are located in regions with a broad climate variability; thus, dealing with these factors is essential to ensure a profitable and sustainable production (Gilbert et al., 2006; Souza et al., 2020; Fattori Junior et al., 2022; Amorim et al., 2022; Althoff and Rodrigues, 2023).

In Brazil, rainfall contributes substantially to supplying the crop water needs in most traditional sugarcane-producing regions; nevertheless, water must be provided from irrigation to fully meet the crop needs in some specific regions. Thus, rights are required to use available surface and underground water resources. Estimates of monthly abstraction flows for water rights are currently calculated using data based on estimations of probable effective rainfall and reference evapotranspiration (ET_o) provided by the Agência Nacional das Águas e Saneamento Básico (ANA) for specific locations and parameters. However, detailed knowledge of the relationships among the components of the soil-water-plant-atmosphere system is necessary for a more accurate estimate in terms of variations in the soil and the production environment (Rocha and Sparovek, 2021; Santiago et al., 2022).

This information allows to verify the levels of water demand that these environments are subject to and the real irrigation needs for optimal crop productivity (Pereira et al., 2021). This detailed procedure is used in the methods proposed by FAO (CROPWAT 8.0), working with a set of total climatological data (standard method) or with just a few chosen years (simplified method). However, this latter option is susceptible to problems due to the uncertainty of choosing the representative years (dry, medium, or wet years), limiting the water rights, or raising flows in years of extreme climate events, which cause an increase in demand.

This research aimed to propose and evaluate an alternative method to determine water rights for sugarcane irrigation, which takes considers the temporal variability in climate variables, and to compare the results with the methods practiced by ANA and with the two methods proposed by CROPWAT 8.0.

Materials and Methods

Study site

The study was conducted at the Rio Claro Unit of Odebrecht Agroindustrial, located in the municipality of Caçú, Goiás State, Brazil (18°33′19″ S, 51°08′06″ W, altitude 486 m). This unit has a crushing capacity of 4.5

million Mg of sugarcane per year, production of 420,000 m^3 of ethanol per year, and generation of 480 GWh of bioelectricity with the excess of plant biomass.

In order to estimate the flow at irrigation catchment, an average annual area of 30,000 ha of sugarcane cultivation was considered for this unit. This area, which can be irrigated, was divided into three sections at the beginning of the crop cycle, corresponding to the beginning, middle, and end of the growth period (Marin et al., 2021). Three soil types were considered in each season, with an available water capacity (AWC) of 50, 100, and 150 mm m^{-1} (Table 1).

For the generation of a 31-year series of climate parameters necessary to calculate daily evapotranspiration by the FAO Penman-Montheith method, the readings from three neighboring Instituto Nacional de Meteorologia (INMET) stations (Table 2) were obtained and averages were calculated. We used values obtained at the Itarumã rainfall station, 38 km away from the site, for daily rainfall. ET_o values were adjusted to a normal distribution and associated to the probability of non-overcoming (P %, probability of occurrence less than or equal to a certain value). Three typical years (wet, medium, and dry) were chosen for the frequency analysis for total rainfall.

Method adopted by ANA

To request a permit for the right to collect water for irrigation from a federal river, it is required to fill out a worksheet at Cadastro Nacional de Usuários de Recursos Hídricos (CNARH). This worksheet is available on ANA website and is used to estimate the monthly demands for water abstraction and use in irrigation. Estimates of water demand consider the needs at different stages of crop development through a simplified local water balance, irrigation efficiency, irrigated area, and irrigation calendar to determine the monthly water abstraction requirements for irrigation. Soil water storage parameters are not used in this balance. The meteorological data and agronomic parameters needed to complete the worksheet are provided by ANA upon request to the technician responsible to grant the request. For these data, ANA uses the FAOCLIM meteorological database, which contains data from 1,503 stations with rainfall and 798 with ET_o (monthly averages) in the Brazilian territory. The New_LocClim software was used to interpolate these data for the specific location of the project.

The method used to estimate ET_o and crop evapotranspiration (ET_c) is proposed by Allen et al. (1998), employing the equation $ET_c = ET_o K_c$. An adjustment coefficient, *kaj*, equal to 0.9, is also proposed for deficit irrigation. Precipitation probability (Pp %) is estimated by a historical series that ensures 80 % of reliability. Effective precipitation, which is the amount available to plants, is determined by using an empirical formula, while the probable effective monthly precipitation combines the two previous definitions. The system application efficiency must be compatible with ANA Resolution 707 of 2004, which presents minimum indicators for the rational use of water.

The default CROPWAT 8.0 template (FAO)

The CROPWAT 8.0 model is a computer program that calculates the water needs of a crop and its irrigation needs, using inputs of climate data (meteorological elements), soil parameters, and crop parameters. The program allows to plan and schedule irrigation for different management criteria and approaches. FAO developed the CROPWAT 8.0 software to estimate water demand worldwide in medium to large irrigated perimeters . All calculation procedures in CROPWAT 8.0 are based on FAO recommendations set out in publication No. 56 (Allen et al., 1998) and No. 33 (Doorenbos and Kassam, 1979).

Table 1 – Division of the area considered representative and irrigated for three cycle start times and three soil types, according to available water capacity (AWC).

Soil	Season 1 - (01 Apr)	Season 2 - (01 July)	Season 3 - (01 Oct)	Total
Type 1 (AWC 50)	1/9 (3,333.3 ha)	1/9 (3,333.3 ha)	1/9 (3,333.3 ha)	1/3 (10,000.0 ha)
Type 2 (AWC 100)	1/9 (3,333.3 ha)	1/9 (3,333.3 ha)	1/9 (3,333.3 ha)	1/3 (10,000.0 ha)
Type 3 (AWC 150)	1/9 (3,333.3 ha)	1/9 (3,333.3 ha)	1/9 (3,333.3 ha)	1/3 (10,000.0 ha)
Total	1/3 (10,000.0 ha)	1/3 (10,000.0 ha)	1/3 (10,000.0 ha)	9/9 (30,000.0 ha)

ha = hectare.

Table 2 – Description of meteorological stations considered in this study.

	Municipality – State			
	Jataí – GO	Rio Verde – GO	Paranaíba – MS	Itarumã – GO
Operating agency		INMET		ANA
Code	83464	83470	83565	1851002
Station type		Full conventional station		Rain station
Latitude	17.91° S	17.80° S	19.75° S	18.76° S
Longitude	51.71° W	50.91° W	51.18° W	51.35° W
Altitude (m a.s.l.)	662.86	774.62	331.25	424.00

GO = Goiás; MS = Mato Grosso do Sul; INMET = Instituto Nacional de Meteorologia; ANA = Agência Nacional de Águas e Saneamento Básico.

The main features and functionality of CROPWAT 8.0 include:

• Entry of meteorological data on a monthly, ten-day, or daily time scale to calculate probability of effective precipitation and ET_o.

• Estimates of crop water and irrigation needs on a ten-day or daily time scale based on updated algorithms (models), including the possibility of adjusting the crop coefficient (K_c) value.

• Planning, programming, and creating a calendar for irrigation management according to the criteria and approaches adopted in the simulations.

• Data output in tabular format with the crop water balance on a daily time scale.

The CROPWAT 8.0 model has been widely used as a tool in the planning and management of water in agricultural systems, including public irrigation perimeters financed by the World Bank, through estimates of crop water requirements and irrigation needs, as well as for estimating relative productivity reductions under water deficit conditions. CROPWAT comprises eight input and output modules: climate/ET_o, rain, crop, soil, crop pattern, CWR (10-day irrigation need), schedule and scheme. Data entry in the climate/ET_o module of CROPWAT 8.0 was carried out in two ways to allow year-by-year simulations of the entire 31-year historical series and a service level of 50 % or 80 % in atmospheric demand.

Data entry in the rain module of CROPWAT 8.0 was performed to allow year-by-year simulations of the entire 31-year historical series (standard method). The model has a routine that calculates the precipitation available for the plants (effective precipitation).

Only the ratoon cane cycles over 365 days were considered when entering data in the crop module. The values used worldwide by FAO were proposed by Doorenbos and Kassam (1979) and Allen et al. (1998), as shown in Table 3. In the simulations carried out year-by-year, three times related to the beginning of the growth cycle were adopted (sprouting and beginning of stumps): 01 Apr, 01 July, and 01 Oct.

Table 3 – Reference values for crop coefficient (K_c), effective root system depth (Z), soil water availability factor (p) and water deficit sensitivity coefficients (ky) throughout the growth and development phases of the crop.

Phase	Days	Kc	Z**	p	ky
Initial	30	0.40	1.0	0.65	0.50
Development	60	-	1.0	0.65	0.75
Intermediate	180	1.25	1.0	0.65	1.20
Final	95	0.75*	1.0	0.65	0.10
Total cycle	365	-	-	-	1.20

Source: Doorenbos and Kassam, 1979; Allen et al., 1998. *Value refers to the end of the final phase and, consequently, of the cycle. **Value refers to the ratoon cane cycle with a previously established root system.

When entering data for the soil module, three types of soil were selected, namely: AWC50 (50 mm m^{-1}), AWC100 (100 mm m^{-1}), and AWC150 (150 mm m^{-1}), all allowing an effective root system depth of 1 m. The remaining soil-related input parameters were fixed for all three soil types. The value of 30 mm d^{-1} was adopted for the maximum rain infiltration rate. The maximum rooting depth was fixed at a standard value of 900 cm and the initial soil moisture depletion, which represents the relative deficit of water storage in the soil at the beginning of the crop growth period, was considered null (0 %), which meant that the soil profile was at field capacity at the beginning of the simulations. Thus, the initial available soil moisture was considered equal to the value of the AWC, for each soil type studied.

In the schedule module, where irrigation management is planned, two types of management were adopted: supplementary irrigation, in which the crop demand is fully met with effective precipitation plus irrigation, and deficit irrigation, which aims to meet the crop demand partially. In the latter case, there is a reduction in ET_c, known as real evapotranspiration (ET_r), calculated through the adoption of a water stress coefficient (K_s). The necessary flows for supplementary (potential) and deficit irrigation are also calculated.

CROPWAT 8.0 model applied in a simplified way

Given the lengthy procedure of the year-to-year water balance, the simplified method proposed by FAO suggests working with only three years (wet, medium, and dry) based on total annual precipitation (TAP) with an attainable probability of 20, 50, and 80 %: (i) TAP-20 % (wet year with theoretical probability achievable by the irrigation system of 20 %); (ii) TAP-50 % (average year with attainable theoretical probability of 50 %); and (iii) TAP-80 % (dry years with attainable theoretical probability of 80 %). In the case of rainfall, instead of entering data for all 31 years, three typical years were chosen as examples of wet, medium, and dry years in terms of total annual rainfall, for which the frequency analysis was carried out.

Proposed alternative method

The fourth method proposed requires that the data entry of the three years into the CROPWAT 8.0 model (wet, medium, and dry) for the frequency analysis include only the accumulated precipitation in the dry period of each year (from Apr to Sept), instead of using the total annual period, as used in the simplified FAO CROPWAT 8.0 method. This procedure identifies the dry periods that reduce crop productivity more accurately.

Results

The ET_o values followed the variation of global solar radiation in the region and the averages ranged from 3.5 to 5.0 mm d^{-1}. Solar radiation is an essential input variable to estimate the water demand of crops in the field, and variation in solar radiation affects the water and energy balance, reflected in differences in ET_o (Pereira et al., 2015; Paredes and Pereira, 2019), as observed in this research (Figure 1).

It was observed that for 80 % probability of not exceeding (less than or equal to) the limit, the maximum values were around 5.6 mm d^{-1}. Considering an application efficiency of 80 % and an average K_c of 1.0 (average value considering three planting times), and excluding water storage in the soil, an approximate water demand of 0.81 L s^{-1} ha^{-1} was obtained, which needs to be supplied by rain and irrigation in Sept and Oct (Figure 2).

The analysis of the average behavior and sample standard deviations of the total effective annual precipitation, for a ten-day period, as well as the monthly average accumulated as a function of the total historical series available, showed that the rainfall contribution for the months of greater evapotranspiration (Sept and Oct) was around 65 mm $month^{-1}$ or 0.25 L s^{-1} ha^{-1} (Figure 3). This means that supplementary irrigation must provide about 0.56 L s^{-1} ha^{-1} to reach the approximate water requirement of 0.81 L s^{-1} ha^{-1} calculated for that period, or about two-thirds of the water requirement. Thus, although it is estimated for the region that irrigation only contributes to 400 to 500 mm yr^{-1} for a total annual sugarcane demand of 1,800 mm yr^{-1}, for the time of greater water need, the contribution of irrigation is crucial (Gasparotto et al., 2022; Gonçalves et al., 2022).

The dispersions of flows for water rights, simulated year-by-year for 31 years by the CROPWAT 8.0 model, assuming supplementary irrigation of the total area (30,000 ha), and the flows for water rights are represented in terms of % of service can be seen in Figures 4 and 5, respectively. For a service percentage

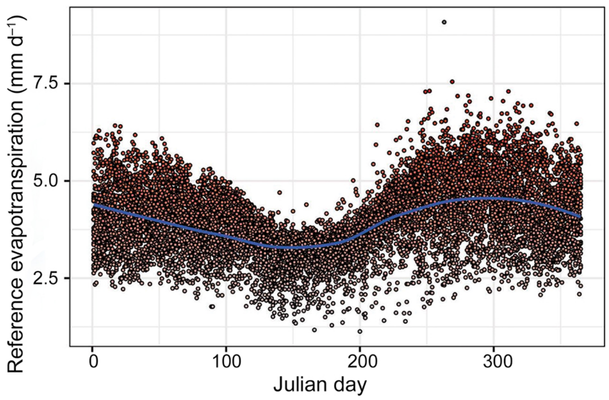

Figure 1 – Central tendency and dispersion of daily reference evapotranspiration (ET_o) values over a one-year period calculated by the Penman-Monteith model for a series of 31 years.

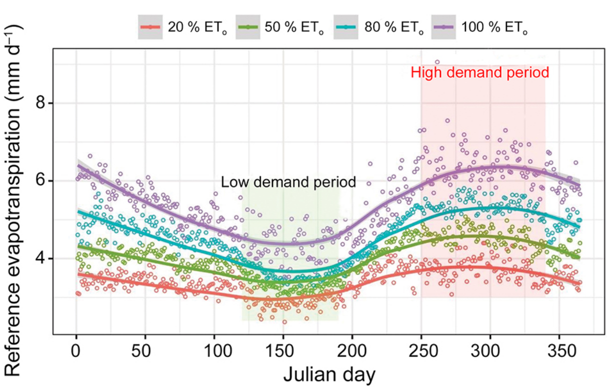

Figure 2 – Daily reference evapotranspiration (ET_o) values with probability P (%) of non-overcoming.

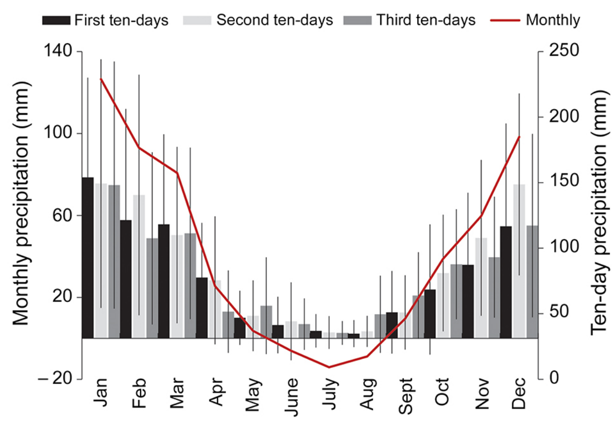

Figure 3 – Mean values and sample standard deviations of ten-day and monthly effective precipitation.

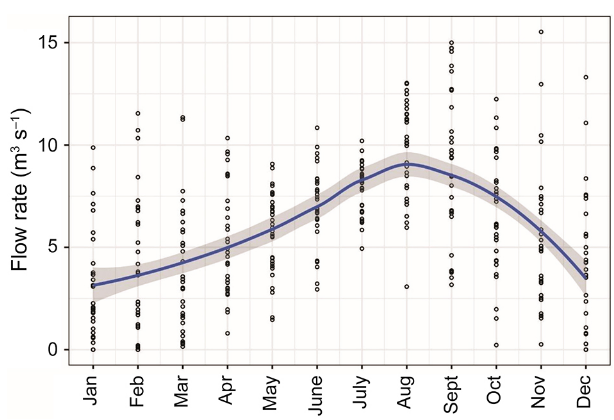

Figure 4 – Dispersion of the monthly flows for water rights (m^3 s^{-1}), considering the total cultivated area (30,000 ha) and year-to-year simulations, with supplementary irrigation.

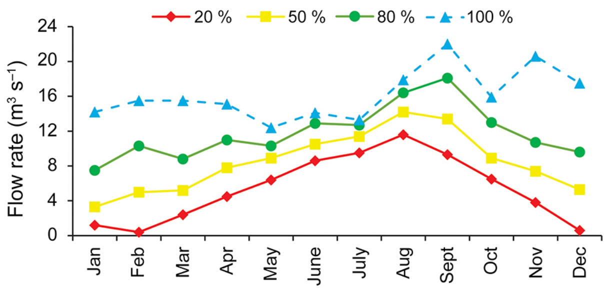

Figure 5 – Monthly values for water rights with different theoretical probabilities of non-overcoming (m^3 s^{-1}), considering the total cultivated area (30,000 ha) with supplementary irrigation.

of 80 % with a return period of five years, the peak occurs in Sept, with a total flow of 18.1 m^3 s^{-1}, which represents a specific demanded flow of 0.603 L s^{-1} ha^{-1}, a value that satisfactorily approaches (Marin et al., 2020) the 0.56 L s^{-1} ha^{-1} approximation previously obtained. The minimum flow occurs in the month of Jan with a specific value of 0.25 L s^{-1} ha^{-1}.

The flows of water rights obtained by CROPWAT 8.0 applied in a simplified way for the dry, medium, and wet years (Yr_{dry}, Yr_{medium} and Yr_{wet}) considering two ET_o service levels (50 and 80 %), with these three years, were selected depending on the total annual period or just the dry period (P_{total} or P_{dry}) (Figure 6). For 80 % Yr_{dry} P_{total}, the maximum demand occurs in the month of Sept, with a flow of 15.6 m^3 s^{-1} for the total area, or 0.52 L s^{-1} ha^{-1} an underestimation occurs in relation to the year-on-year. For 80 % Yr_{dry} P_{dry} (method proposed in this work), the maximum demand occurs in the month of Jan, with a flow of 17.1 m^3 s^{-1} for the total area or 0.57 L s^{-1} ha^{-1} and the minimum occurs in March, with a value of 0.33 L s^{-1} ha^{-1}.

Regarding the flows for water rights in the total area according to ANA spreadsheet, it was found that the maximum demanded flow occurs in Aug and Sept, reaching 16.2 m^3 s^{-1} for the total area, or 0.54 L s^{-1} ha^{-1}. The minimum occurs in Dec, with a value of only 0.16 L s^{-1} ha^{-1}, which represents an underestimation of the minimum of 36 % in relation to the year-on-year method with CROPWAT 8.0 (Figure 7).

The flows for water rights calculated by the CROPWAT 8.0 program year-by-year (standard method) for the total series of 31 years for the case of deficit irrigation can be seen in Figure 8. The monthly flows calculated by the CROPWAT 8.0 program are presented according to the % of attendance. For 80 % of service, it appears that the highest demand occurs in Sept, with a total flow of 12.73 m^3 s^{-1}, representing a specific demand of 0.42 L s^{-1} ha^{-1}. The minimum flow assumes a value of 0.18 L s^{-1} ha^{-1}, occurring in the month of Jan. Compared to supplementary irrigation, deficit irrigation decreased 29.7 % for the maximum flow and 28 % for the minimum flow (Figure 9).

The flows for water rights obtained by CROPWAT 8.0 applied using the simplified method for the dry,

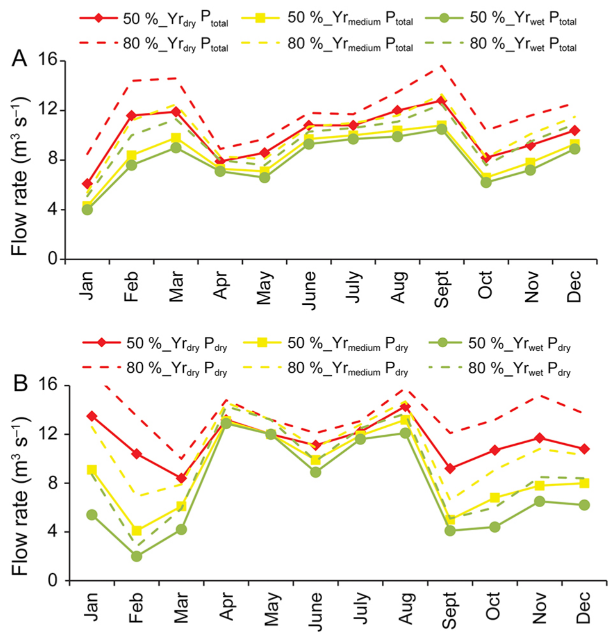

Figure 6 – Monthly values for water rights (m^3 s^{-1}) for the contrasting years considering the total cultivated area (30,000 ha) with supplementary irrigation. Yr_{dry}, Yr_{medium} and Yr_{wet} = dry, medium and wet years; P_{total} and P_{dry} = total annual period and dry period.

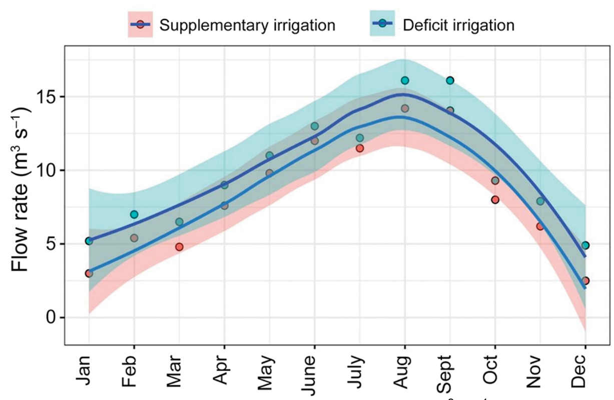

Figure 7 – Average flows for water rights (m^3 s^{-1}) considering the Agência Nacional de Águas e Saneamento Básico (ANA) spreadsheet and total cultivated area (30,000 ha) with supplementary and deficit irrigation.

medium, and wet years (Yr_{dry}, Yr_{medium} and Yr_{wet}), considering two levels of ET_o service (50 and 80 %) can be seen in Figure 10. These three years were selected according to the total annual period or only the dry period (P_{total} or P_{dry}); the P_{dry} method was used in this work. For 80 % Yr_{dry} P_{total}, the maximum demand occurred in Sept, with a flow of 11.88 m^3 s^{-1} for the total area or 0.40 L s^{-1} ha^{-1} (underestimation of the maximum of 6.7 % in relation to the standard). As for 80 % Yr_{dry} P_{dry} (proposed method), the maximum demand occurred in Aug, with a flow of 12.96 m^3 s^{-1}. The minimum, for 80 % Yr_{dry} P_{dry}, is 0.27 L s^{-1} ha^{-1}.

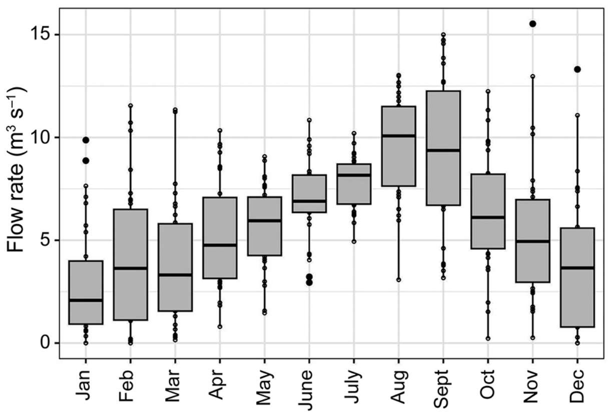

Figure 8 – Box plot of the monthly flows for water rights (m^3 s^{-1}), considering the total cultivated area (30,000 ha) and year-to-year simulations with deficit irrigation.

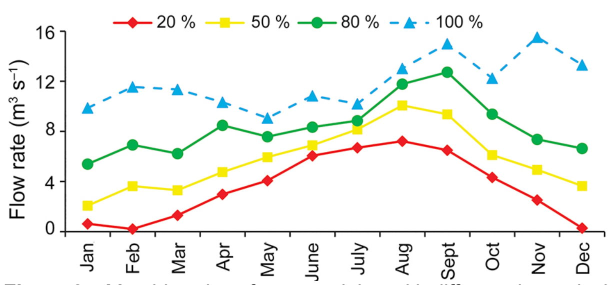

Figure 9 – Monthly values for water rights with different theoretical probabilities of non-overcoming (m^3 s^{-1}), considering the total cultivated area (30,000 ha) with deficit irrigation.

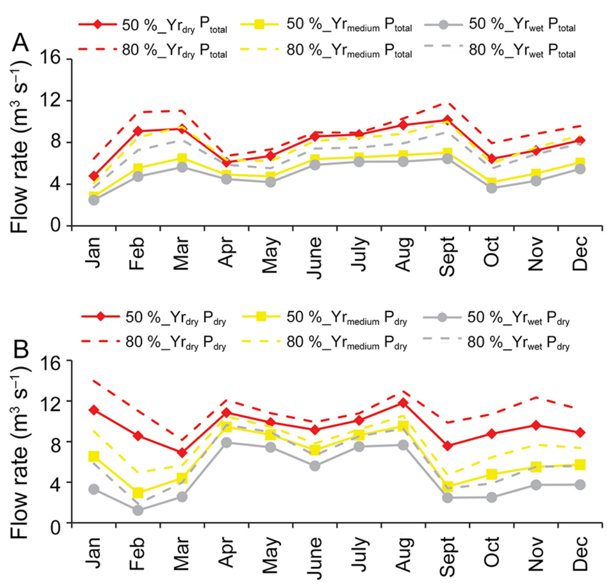

Figure 10 – Monthly values for water rights (m^3 s^{-1}) for the contrasting years, considering the total cultivated area (30,000 ha) with deficit irrigation. Yr_{dry}, Yr_{medium} and Yr_{wet} = dry, medium and wet years; P_{total} and P_{dry} = total annual period and dry period.

Regarding the flows for water rights for the total area according to ANA spreadsheet for deficit irrigation, the maximum demanded flow occurred in Aug and Sept, reaching 14.56 m^3 s^{-1} for the total area or 0.49 L s^{-1} ha^{-1} (Figure 7). The minimum occurred in Dec with only 0.09 L s^{-1} ha^{-1}, which represents an underestimation of the minimum of 51.9 % in relation to the year-on-year method. Variations in demanded flows are due to significant changes in meteorological variables that directly affect the availability of natural water for crops throughout the year, mainly in tropical regions, with rainfall concentrated in spring and summer (Oct to Feb) and a well-defined dry season from June to Sept (Tukimat et al., 2017; De Graaf et al., 2014; Shahdany et al., 2019).

Discussion

The method to calculate flows for water rights proposed by ANA underestimates the minimum irrigation demand (rainy season) from 36.0 to 51.9 % compared to the CROPWAT 8.0 method, performing a year-by-year water balance (standard method with 31-year series). The ANA method does not provide operational security to large enterprises, especially in the rainy season, since it needs an adequate probabilistic character that considers the annual variations in precipitation.

On a worldwide scale, water rights regulatory agencies and corresponding markets work to address water scarcity by establishing tradable, limited-access permits to water resources. The broader insights of this research suggest that when rights holders accurately assess water demand, optimal engagement strategies can be developed that add to farm-scale profitability and allow to determine whether existing rights ownership matches risk tolerance (Fachinelli and Pereira Junior, 2015; Delorit et al., 2019; Eshete et al., 2020; Portoghese et al., 2021).

Integrated water resource management methods and tools have been developed to reflect how different water resources managers and users perceive problems and predict possible long-term impacts. Criteria that do not take into account an analysis of temporal variability (year-by-year analysis) are no longer sufficient to face the challenges related to water management in the Brazilian agricultural system (Bronstert et al., 2000; Krol et al., 2001; Fachinelli and Pereira Junior, 2015).

The simplified method proposed by FAO (CROPWAT 8.0), due to the criteria to choose the three representative years (dry, medium, and wet), had a good performance in the wet period. However, it resulted in underestimating the maximum demanded flow from 6.7 to 13.8 % in the dry period when compared to CROPWAT 8.0 applied year-on-year. The FAO simplified method was subject to vulnerabilities since it does not take into account the variability of the monthly rainfall distribution in the selection of the year taken as a basis.

Estimation of water requirements is vital to designing and operating an agricultural water resource system. Techniques, such as FAO simplified method, are used to estimate the high spatial and temporal hydrological variable of water demand. This is certainly an advance over methods that did not have an adequate probabilistic character; however, it is still important to interpret these estimates properly to ensure practical information to water resource managers (Fernandes et al., 2019; Parsinejad et al., 2022).

The alternative method to the year-by-year balance proposed here allows a more accurate estimation of the demanded flow for irrigation, mainly in the dry period of the year, providing a slight overestimation in the wet period (from 5.1 to 7.5 %) when compared to the FAO standard method. Notably, this period coincides with the highest supply of water bodies, which leads to the conclusion that the more detailed approach of the proposed method , considering monthly values, can optimize supplementary or deficit irrigation strategies in years where rainfall is below average. This ensures a better-balanced use of water in months when there is a surplus in the water courses, contributing to the stability and security of the agricultural farm. In the dry period, the method proposed also showed a satisfactory performance.

The comparison between supplementary irrigation and deficit irrigation, based on simulations carried out year-by-year on the FAO model (the standard method of the 31-year series), showed that irrigation with a deficit promotes a saving of about 30 % in the water resource demand for the region under study, regarding irrigation of the sugarcane crop.

Our results show that the alternative method to the year-by-year balance proposed in this investigation allows a more accurate estimation of the demanded flow for sugarcane irrigation in Brazil, when compared with the ANA method. The simplified method proposed by the FAO (CROPWAT 8.0) performs well but displays some vulnerability. We verified that the proposed method helped improve water resource management in Brazil and worldwide. This method could also be used as a benchmark to validate other methods that governments, regulatory agencies, research institutions, and others may suggest.

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Authors' Contributions

Conceptualization: Maschio R, Coelho RD. **Data curation:** Maschio R, Coelho RD. **Formal analysis:** Maschio R, Coelho RD, Barros THS. **Funding acquisition:** Coelho RD. **Investigation:** Maschio R, Coelho RD, Barros THS, Costa JO, Duarte SN. **Methodology:** Maschio R, Coelho RD. **Project administration:** Maschio R, Coelho RD. **Resources:** Coelho RD. **Supervision:** Coelho RD. **Writing-original draft:** Maschio R, Coelho RD, Barros THS, Costa JO, Duarte SN. **Writing-review & editing:** Maschio R, Coelho RD, Barros THS, Costa JO, Duarte SN.

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