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Recharge assessment in the context of expanding agricultural activity: Urucuia Aquifer System, western State of Bahia, Brazil

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Abstract
Groundwater recharge rate estimation is crucial to sustainable development of aquifers in intensely pumped regions, such as the Urucuia Aquifer System (UAS). A sedimentary aquifer in Western Bahia, Brazil, that underlies one of the major agricultural areas of the country where there has been major growth of irrigated areas. This study seeks to evaluate the recharge component of the water budget in the UAS area, based on three complementary techniques. The double-ring infiltrometer test was used to evaluate surface infiltration capacity, an important control on recharge. Water level data from wells (2011–2019 period, 19 wells) in the Brazilian Geological Survey's Integrated Groundwater Monitoring Network (RIMAS-CPRM) was used to estimate the aquifer recharge using the water table fluctuation (WTF) method. Additionally, this study used the Soil Water Assessment Tool (SWAT) model in two selected sub-basins to estimate deep recharge from the surface hydrological data. The results of the infiltrometer tests show a notable difference in the infiltration rates between the natural vegetation zones and cropped areas. The WTF and SWAT simulations results suggest similar ranges of recharge rate (an average of 24% of precipitation, in both methods). Results of the study indicate equivalence of these methods to estimate the recharge in sedimentary unconfined aquifers as UAS.

Keywords: Groundwater recharge, Agriculture, Urucuia aquifer system, Soil water assessment tool

1. Introduction

The region of MATOPIBA, which includes the Cerrado biome (Brazilian Savannah) in the states of Maranhão, Tocantins, Piauí, and Bahia, comprises areas where the topography and climate have favored the development of large-scale agriculture (**Fig. 1**). This region stands out as one of the main agricultural frontiers in Brazil, mainly in the western portion of Bahia state.

The western regions of Bahia experienced an important agricultural expansion in recent decades, becoming the main agricultural frontier of the state and one of the most important in Brazil. Bahia is now a major national producer of soybeans, corn, cotton, coffee, and fruits (Donagemma et al., 2016). This process led to substantial changes in the land use of this region and has created an intense exploitation of water resources (Brannstrom, 2005; Oliveira et al., 2017a, 2017b).

In the last 30 years, the increased demand for irrigation water in Western Bahia has led to a reduction in water availability of some surface water sources in the region, causing some rivers to reach legal limits of exploitation ("maximum exploitation"; Gaspar and Campos, 2007; Pousa et al., 2019; Marques et al., 2020). Despite the increased

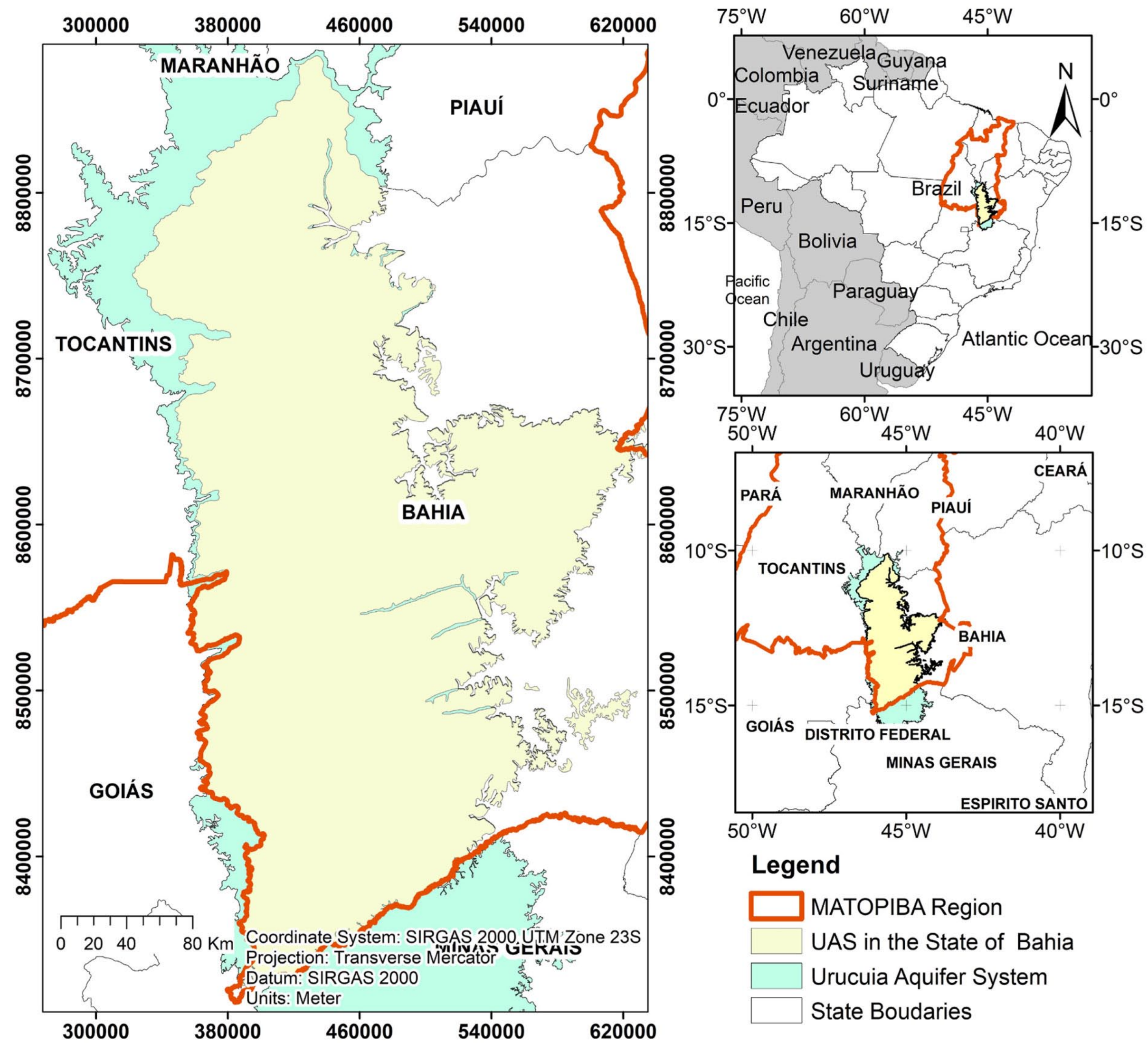

Fig. 1. Location of the Urucuia Aquifer System (UAS) (*in light green*) in MATOPIBA region and UAS on Bahia State, Brazil (*in yellow*).

use of this resource, groundwater remains a strategic resource in this region, responsible for up to 95% of the discharge in local rivers during the dry season (Gonçalves et al., 2018; Gonçalves et al., 2016).

The infiltration process affects surface runoff, soil erosion, and groundwater recharge (Gregory et al., 2005). Understanding how changes in land use and crop production management practices affect the infiltration rates, as well as improved estimates of recharge rates, are keys for sustainable development of the agricultural and water resources within the UAS area.

The main goals of this study were to assess possible alterations in the infiltration capacity caused by changes in the land use and cover, and to estimate the recharge rates in the UAS region. These objectives were accomplished using (1) double-ring infiltrometer tests to verify the infiltration capacity of soils, (2) estimating recharge using the water table fluctuation (WTF) method, and (3) using the process-based Soil Water Assessment Tool (SWAT) model to estimate the recharge.

Estimating groundwater recharge is an important step in resource evaluation, which usually occurs in extensive areas and demands long timescale analysis. This estimation process requires refinement and updates as new data is added (Scanlon et al., 2002). The double-ring infiltrometer, along with soil physical analyses, is widely applied as a technique to evaluate the soil infiltration rates (Touma and Albergel, 1992; Yimer et al., 2008; Ruggenthaler et al., 2016; Li et al., 2019).

The water table fluctuation method allows for the estimation of the average groundwater recharge using the precipitation and water table measurements (Healy and Cook, 2002). This method is acknowledged worldwide to evaluate the recharge and brings satisfactory results in shallow aquifer and in regions where the water table variation occurs seasonally (Crosbie et al., 2005; Fan et al., 2014; Águila et al., 2019).

The SWAT model is a continuous-time, semi-distributed, and processed-based model developed by the United States Agricultural Research Service to simulate physical changes and the dynamics of water balance, sediment transport, pesticides, and pollutants within watersheds using Hydrological Resources Units (HRUs), which are hydrological response units generated from overlapping land use, soil type, and topography maps (Neitsch et al., 2011; Arnold et al., 2012).

The main purpose of this study was to evaluate the recharge rates in the UAS applying different methods based on *in-situ* tests distributed in the UAS region. Initially a double-ring infiltrometer was used to estimate the surface infiltration at different land use and vegetation cover; in step 2, was calculated the recharge by using the water table fluctuation (WST); thirdly, was calculated the recharge based on SWAT (Soil Water Assessment Tool) for two smaller watersheds; and finally, was compared and discussed all these results to determine the most accurate recharge to be used on hydrogeological modelling (not presented in this study).

2. Materials and methods

2.1. Study area

The study area is mainly located in the western area of the State of Bahia - Brazil, extending for 82,000 km^2, and comprising 68% of UAS (**Fig. 2**). The UAS is situated in northeastern Brazil and extends through five states, from the southern portion of Maranhão and Piauí States, through western Bahia, northeastern Goiás, southeastern Tocantins, and northern Minas Gerais states (Gaspar and Campos, 2007).

The UAS, which is a great groundwater reservoir with mostly unconfined behavior, is located within the Cretaceous geological unit - Urucuia Group. The Urucuia Group is composed of two formations: at the base, the Posse Formation is characterized as an Aeolian sandstone with cross-stratifications from large dunes and a horizontal stratification in friable and fine to medium grain size sandstones, intercalated with clays and silts. Above the Posse Formation is the Serra das Araras Formation, composed of fluvial texturally heterogeneous deposits of medium to thick sandstones. In some areas, the sandstone recrystallizes, forming extensive silicified but thin layers with low permeability, typically occurring near the contact with Posse Formation (Campos and Dardenne, 1999; Amorim Júnior and Lima, 2007; Barbosa et al., 2017).

This region is composed by four watersheds (Fig. 2 A), Middle and Upper Grande River, Corrente River, and Carinhanha River. The UAS is responsible for 80%–97% of these rivers’ baseflow (Gonçalves et al., 2018), which flow to north-northeast towards the São Francisco River. In Western Bahia, the long-term average precipitation was 1060 mm/year, between 1980 and 2015. During the dry season (June, July, August) the precipitation varies from 0 to 10 mm/month, and in the rainy season (December, January, February), 150–200 mm/month (Pousa et al., 2019).

The percolation from precipitation is the major source of groundwater recharge for the UAS. The rainy season occurs between the months of November and April, and it represents an accumulated average of 1200 mm/year. Rainfall events happen both in intense and short-term occurrences. After these events, some water leaves system by surface runoff into rivers and streams, and by evapotranspiration.

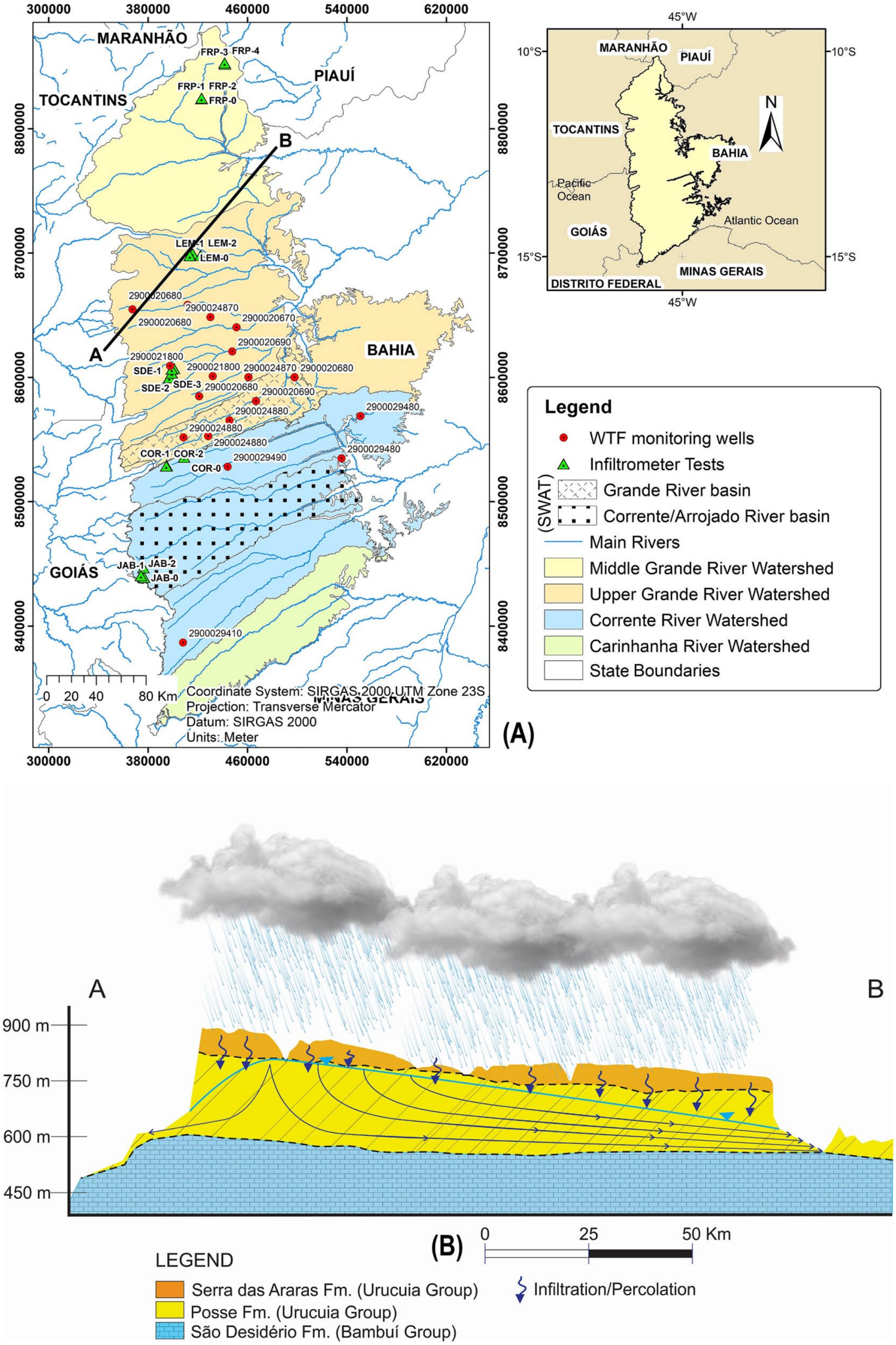

Fig. 2. (A) Location of the four watersheds in the study area, of the infiltrometer tests, the monitoring wells for WTF method, and the sub-basins for SWAT models; (B) Hydrogeological Conceptual model of the study area (cross-section A-B of Fig. 2A).

The infiltrating portion will remain in the shallow soil layer, gradually moving vertically through subsurface materials, resulting in UAS recharge (Fig. 2 B).

2.2. Double-ring infiltration test

The study was conducted in some areas of the UAS, within the cities of Correntina, Formosa do Rio Preto (Coaceral locality), Jaborandi, Luís Eduardo Magalhães, and São Desidério (Roda Velha locality), with two areas located in the Corrente River watershed and five in the Middle and Upper Grande River watershed. A total of 208 infiltration tests were performed in 17 areas with distinct characteristics (Fig. 2). In each area, were performed eight tests in the dry and rainy seasons.

The study sought to evaluate the infiltration capacity of the soil in the following different soil use areas: non-cultivated, with Cerrado vegetation (Brazilian Savannah), and in areas cultivated under different cropping systems. For the identification of the tests, each one was assigned a three-letter code and a number, the letters to denote the municipality where it is located and the number to denote the type of land use (**Table 1**).

Table 1 Test code and soil description (Land Use and Soil management).

Test Code ID	*Land Use; Soil Management*
FRP-0	Cerrado (Brazilian Savannah); Native vegetation
FRP-1	Crop; soil mobilized before the planting of the 2017/2018 production season
FRP-2	Crop; No-till since 2015
FRP-3	Crop; No-till since 2004
FRP-4	Crop; No-till since 2002
LEM-0	Cerrado (Brazilian Savannah); Native vegetation
LEM-1	Crop; soil mobilized before the planting of the 2017/2018 production season
LEM-2	Crop; No-till since 2010
SDE-0	Cerrado (Brazilian Savannah); Native vegetation
SDE-1	Crop - soil mobilized before the planting of the 2017/2018 production season
SDE-2	Crop - No-till since 2016
SDE-3	Crop - No-till since 2015
COR-0	Cerrado (Brazilian Savannah); Reflorestation since 2003 (Natural regeneration)
COR-1	Crop - soil mobilized before the planting of the 2017/2018 production season
COR-2	Crop - No-till since 2016
JAB-0	Cerrado (Brazilian Savannah); Native vegetation
JAB-1	Crop - soil mobilized before the planting of the 2017/2018 production season
JAB-2	Crop - No-till since 2014

Obs.: FRP - Formosa do Rio Preto; LEM – Luis Eduardo Magalhães; SDE – São Desidério; COR – Correntina; and JAB – Jaborandi.

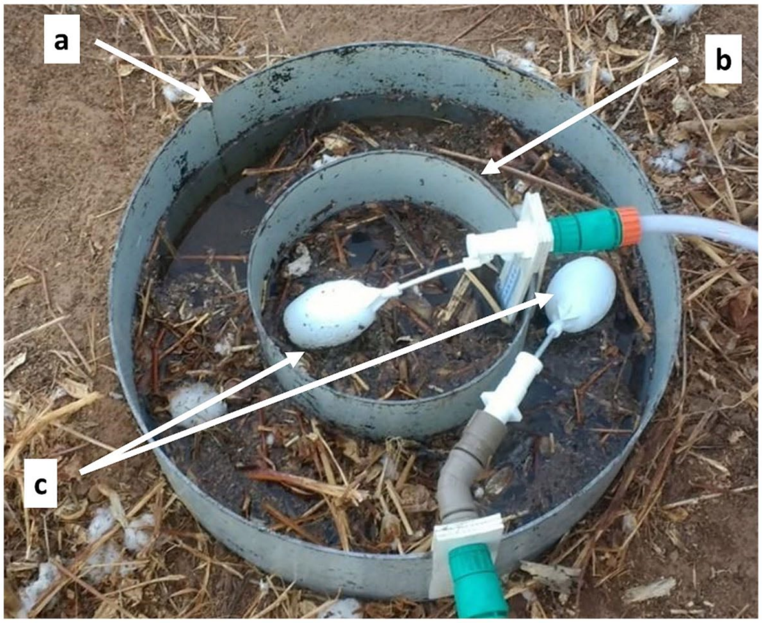

Fig. 3. Example of infiltration test performed on cropped areas in UAS region. System description: **a)** Outer ring, **b)** Inner ring, **c)** Floats valves.

The infiltration capacity of the soils was determined by infiltration tests using semi-automated concentric double-ring infiltrometer 250 mm (inner) and 500 mm (outer), using float valves to maintain a constant head during the tests (**Fig. 3**). The water supply in the inner and outer rings was provided by water reservoirs connected to the float valves. The inner ring feed reservoir was equipped with a millimeter scale to measure the infiltrated water over time.

The variable analyzed was the steady infiltration rate (SIR) of the soil, corresponding to the rate obtained after the stabilization of the infiltration process. The duration of each test was defined according to the time required for the stabilization of the process, through detailed observation of the variation of the infiltration rate during the test, seeking to get at least five equal values for the infiltration rate before the end of each test (Bernardo et al., 2006). One of the main limitations of this method is that the water that flows within the infiltration ring flows both horizontally and vertically through the ground, which can yield greater results than if the flow were confined vertically. Corrections may be applied, however, for comparative purposes they are not necessary.

It is important to make a distinction between the measured infiltration rates in the field and the consequent aquifer recharge. The recharge to a water-table aquifer is the flow of infiltration through the unsaturated zone up to the saturated zone. Factors like the depth to water table, unsaturated zone stratification, air entrapment, and topography have a significant role in the actual recharge, especially when transient flow problems are concerned, and hypodermic or lateral flow can be significant in some cases (Besbes and De Marsily, 1984; Loizeau et al., 2017).

The average infiltration rate of the point was determined by the arithmetic mean of the rates in the eight tests, and the confidence intervals were calculated using the Student's t-distribution, at a confidence level of 95%. This test calculates the infiltration rate of the soil pointily, and spatial changes in land use and soil type can affect the results.

During the rainy season, between January and June 2018, soil samples were collected at the same locations where infiltration tests were conducted, at the depth of 0–45 cm. Disturbed soil samples were collected for granulometric analysis, and undisturbed samples were used to determine some parameters in laboratory such as, macroporosity, microporosity, total porosity and soil bulk density (Donagemma et al., 2011).

The samples were collected in the same locations where these tests were conducted, except for the SDE-3 area, where the soil collection could not be performed because soil mobilization occurred before the team returned to the property. Conversely, an additional area, FRP-3, conducted under no-tillage, was sampled as infiltration tests had not been carried out. In each area, 27 disturbed and undisturbed soil samples were collected. The means of each parameter were calculated by the arithmetic mean of the values obtained in the 27 samples, and the confidence intervals were calculated using the Student's t-distribution, at a confidence level of 95%.

2.3. Water table fluctuation (WTF)

The WTF method uses variations in the groundwater level over time to estimate the recharge in free aquifers (Healy and Cook, 2002), and considers that increases in groundwater levels occur due to aquifer recharge. Recharge is spatial parameter, however, and the WTF method is applied only to a specific portion of the aquifer; thus, its representativeness is restricted (Scanlon et al., 2002). Equation (1), which considers that the water reaching the water table immediately enters storage and that all other components of the groundwater balance are null during the recharge period is used when applying the method (Healy and Cook, 2002; Healy and Scanlon, 2010).

$$R = Sy \cdot \frac{dh}{dt} = Sy \cdot \frac{\Delta h}{\Delta t} \tag{1}$$

To carry out the work, this research selected 19 wells for analysis. These wells were among 60 monitoring wells of the Integrated Groundwater Monitoring Network (RIMAS) from the Brazilian Geologic Survey (CPRM), installed in several points on the UAS area, since 2011. The water level depth ranged from 3.9 m to 121 m, and monthly averages of variation, in meters, of the water level in the wells (Δh) were calculated using an arithmetic average, disregarding the months that did not have at least 15 consecutive days of measurement. Based on this criterion, only wells with at least 36 months of data in a period between 2011 and 2019 were used, since the WTF method relies on longer historical records. Another criterion was the number of recession periods, which should be at least two peaks to calculate the WTF.

This study has calculated the Δh for each peak, using the monthly averages of level variation plotted in charts, by calculating the difference between a peak of NA increase and the extrapolation of the lowering curve prior to it. The study used specific yield (Sy) values from the literature (**Table 2**), along with the arithmetic mean of the peaks to calculate the minimum, the average and maximum recharge.

The rain data were obtained from five rainfall stations at Hidroweb site of the Brazilian National Water Agency (ANA), and 12 artificial stations from TRMM (Tropical Rainfall Measuring Mission).

To calculate the recharge by the WTF method, were used 19 wells with satisfactory results (Fig. 2), in which water level records have allowed us a good measurement of the water level variation. The discarded data presented problems such as the lack of data in certain periods, making it difficult to interpret the water level variation curve. In

Table 2 Specific yield (*Sy*) applied on the calculations (Johnson 1967 apud. Healy and Scanlon, 2010).

	Specific yield (%)		
Texture	*Maximum*	*Average*	*Minimum*
Clay	5	2	0
Sandy clay	12	7	3
Silt	19	8	3
Fine sand	28	21	10
Medium sand	32	26	15
Coarse sand	35	27	20
Gravelly sand	35	25	20
Fine gravel	35	25	21
Medium gravel	26	23	13
Coarse gravel	26	22	12

addition, it was not possible to observe some wells because the water level did not seem to respond to the registered rain events, probably because of the dispersion of water during the infiltration process or the presence of a confining layer.

2.4. Water balance and recharge with SWAT

This study used SWAT because it is a tool capable of representing the effect of land use and cover on the water balance and, consequently, in the estimation of groundwater recharge, in watershed scale. Most limitations present in SWAT models are related to the large volume of data required to run the model, such as land use and soil parameters, weather stations and discharge records. Lack of quality data with spatial and temporal resolution can negatively affect model performance and calibration (Akoko et al., 2021).

ArcSWAT is an ArcGIS extension that facilitates the spatial understanding of the work and the process of data entry in the graphical interface. This study performed SWAT simulations for two sub-basins in the region, Grande River basin and Corrente/Arrojado River basin (Fig. 2).

SWAT model calculates the hydrological cycle using the following water balance equation (Equation (2)):

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_{\alpha} - w_{seep} - Q_{gw}) \quad (2)$$

where SW_t is the final soil water content (mm H_2O), SW_0 is the initial soil water content on day i (mm H_2O), t is the time (days), R_{day} is the amount of rain precipitated on day i (mm H_2O), Q_{surf} is the amount of runoff on day i (mm H_2O), E_{α} is the amount of evapotranspiration on day i (mm H_2O), w_{seep} is the amount of percolation exiting the soil profile on day *i* (mm H_2O), and Q_{gw} is the amount of return flow on day i (mm H_2O) (Neitsch et al., 2011).

The water that infiltrates and flows from the bottom of the soil profile through the vadose zone percolates until it reaches the saturated zone and is stored as a recharge for the aquifer. SWAT separates the saturated zone into two aquifers in its system: one unconfined and the other confined (Neitsch et al., 2011). This study consider the value of the total recharge of the two aquifer types, since the UAS is predominantly unconfined, presenting some restricted semiconfined aquifer zones (Gaspar and Campos, 2007). Equation (03) indicates the recharge for both aquifers on a given day is:

$$w_{rchrg,i} = \left(1 - \exp\left[\frac{-1}{\delta_{gw}}\right]\right) \cdot w_{seep} + \exp\left[\frac{-1}{\delta_{gw}}\right] \cdot w_{rchrg,i\text{-}1} \quad (3)$$

where $W_{rchrg,i}$ is the amount of recharge entering the two aquifers on day *i* (mm H_2O), δ_{gw} is the delay time of the overlying geological formation (days), w_{seep} is the amount of percolation exiting the soil profile on day *i* (mm H_2O), and $w_{rchrg,i\text{-}1}$ is the amount of recharge entering both aquifers on the previous day *i*–1 (mm H_2O) (Neitsch et al., 2011).

2.4.1. Configuration, model setup, and input data

SWAT model requires input data related to climate, land use, soil type, and topography. The version used was SWAT2012 with the ArcSWAT interface. The simulation period extended from 2008 to 2019, with the first three years used as warm up to the model, so the results were generated from 2011 to 2019. **Table 3** lists the input data source and resolution.

Table 3 Input data resolution and source.

	Resolution	*Source*
Digital Elevation Model	30 m	Shuttle Radar Topography Mission (SRTM) http://www.webmapit.com.br/inpe/topodata/
Soil	30 m	Embrapa http://geoinfo.cnps.embrapa.br/layers/?limit=100&offset=0 and OBahia http://obahia.dea.ufv.br/layers/?limit=20&offset=0
Land use	30 m	OBahia http://obahia.dea.ufv.br/maps/38/view and MapBiomas https://plataforma.mapbiomas.org/map#coverage
Climate Data	0.25°(TRMM) and 1°(CSFR)	Tropical Rainfall Measuring Mission (TRMM) https://www.agritempo.gov.br/agritempo/index.jsp and National Center for Atmospheric Research (NCAR) https://rda.ucar.edu/pub/cfsr.html
Discharge	Measured	Agência Nacional das águas (ANA) http://www.snirh.gov.br/hidroweb/serieshistoricas

Using the DEM (**Fig. 4**A), SWAT delimited the sub-basins and the stream network. It has generated 21 sub-basins for the Grande River basin, and 22 sub-basins for the Corrente-Arrojado River basin.

The required climatic data are precipitation, solar radiation, temperature, relative humidity, and average wind speed, all on a daily time scale. The study used TRMM (Tropical Rainfall Measuring Mission) satellite data, which is a joint space mission between NASA and JAXA, with the aim of gathering precipitation and temperature data from 18 precipitation stations and 17 temperature stations. It has used values available of reanalysis data from the CSFR (Climate Forecast System Reanalysis) of the National Center for Atmospheric Research (NCAR) to obtain solar radiation, relative humidity, and average wind speed data. To estimate potential evapotranspiration (ETp) in the SWAT model have three methods available (Neitsch et al., 2011) such as the Penman-Monteith method (Monteith, 1965; Allen, 1986; Allen et al., 1989), the Priestley-Taylor method (Priestley and Taylor, 1972), the Hargreaves method (Hargreaves et al., 1985). The potential evapotranspiration was calculated using the Penman-Monteith method.

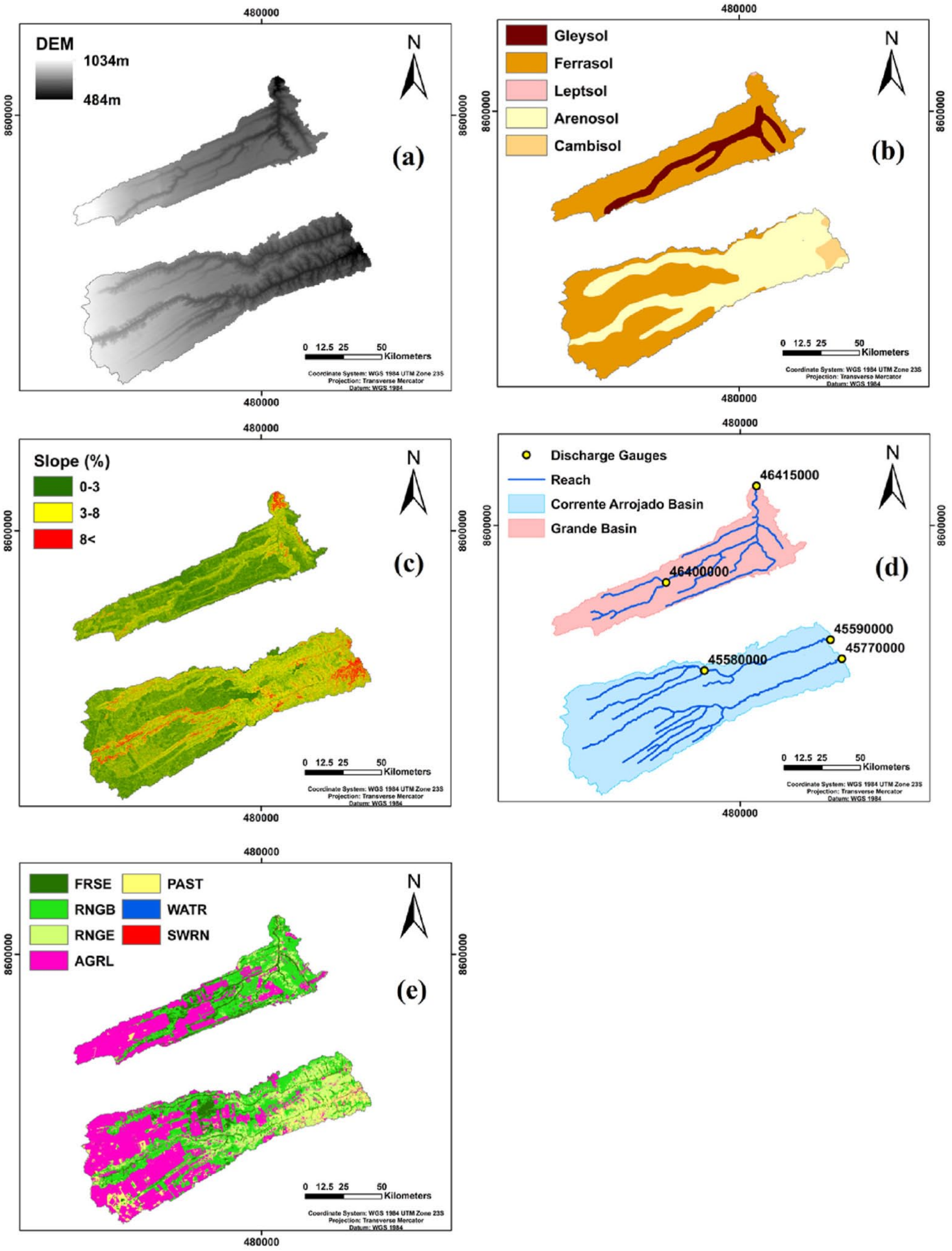

Fig. 4. Input data in SWAT model of Grande River and Corrente-Arrojado River watershed. **a**) Digital Elevation Model with resolution of 30 m obtained from SRTM; **b**) Soil classes obtained from Embrapa (1977); **c**) basins slope map, generated in Arcswat; **d**) Location of discharge gauges used for model calibration; **e**) Basins land use maps obtained, FRSE – Forest Evergreen, PAST – Pasture, RNGB – Range Brush, WATR - Water, RNGE –Range Grass, SWRN - South Western Range Bare- Rock, AGRL – Agriculture (Mapbiomas, 2020).

SWAT requires different input parameters for different soil types and land cover. Jacomine et al. (1976), Baldissera (2005), and Fernandes (2015) provided the soil types parameter data, while SWAT database provided the land use parameters. The slope map classified the study areas into three slope classes: 0–3%, 3–8%, and >8%. After the preparation of land use, soil, and slope maps (Fig. 4B, C and D), SWAT overlaid them to generate the HRUs, resulting in a total of 463 units for the Grande River watershed and 596 for the Corrente-Arrojado River watershed.

Model calibration and validation were based on discharge data from the gauges of the following Brazilian Nacional Water Agency (ANA) stations: Casa Real (46400000) and Sítio Grande (46415000) in the Grande River basin; and Veredão (45580000), Correntina (45590000) and Arrojado (45770000) in the Corrente-Arrojado River. The spatial distribution of the stations is shown in Fig. 4E.

2.4.2. Calibration, validation, and uncertainty analysis

SWAT-CUP (Abbaspour, 2015), an automatic calibration tool, was used to calibrate the model. Within the SWAT-CUP different calibration algorithms are available, which are SUFI-2, ParaSol, PSO, GLUE, and MCMC. The present study selected SUFI-2 (Sequential Uncertainty Fitting, version 2), because it is an algorithm widely used for calibrating hydrological models and requires fewer iterations to reach satisfactory results (Yang et al., 2008).

During calibration with the SUFI-2, SWAT-CUP performs consecutive iterations, trying to achieve the most appropriate adjustment of the model, according to a chosen objective function. Among the 10 objective functions available in SWAT-CUP, the authors have selected Nash- Sutcliffe Efficiency (NSE) (Equation (4)), as it is an objective function widely used in hydrological studies (Nash and Sutcliffe, 1970), and made 500 simulations per iteration. Moriasi et al. (2007) considered values above 0.5 as satisfactory.

Other parameters observed to the model calibration were the PBIAS (Equation (5)) results of and the determination coefficient, R^2 (Equation (6)). The first indicates the tendency of the simulated values to be higher or lower than those observed, with positive values indicating an overestimation of the model, and negative values, an underestimation (Gupta et al., 1999). The second, obtained from the linear regression between the simulated and observed values, is considered satisfactory for values above 0.5 (Bonumá et al., 2014; Chung et al., 2002).

$$NSE = 1 - \frac{\sum_i (Q_m - Q_s)_i^2}{\sum_i (Q_{m,i} - Q_{-m})^2} \tag{4}$$

$$PBIAS = 100 * \frac{\sum_{i=1}^{n} (Q_m - Q_s)_i}{\sum_{i=1}^{n} Q_{m,i}} \tag{5}$$

$$R^2 = \frac{[\sum_i (Q_{m,i} - Q_{-m})(Q_{s,i} - Q_{-s})]^2}{\sum_i (Q_{m,i} - Q_{-m})^2 \sum_i (Q_{s,i} - Q_{-s})^2} \tag{6}$$

where Q_m is the observed variable, Q_s is the simulated variable, Q_{-s} is the average of the simulated variable, and Q_{-m} is the average of the observed variable.

The sensitivity analysis helps to test and select the most sensitive parameters for calibration with an interval of values for each parameter. These values generate a range of uncertainty in the calibration output called 95% prediction uncertainty or 95PPU. The 95PPU is calculated at the 2.5% and 97.5% levels of cumulative distribution of the model output variables. This range decreases with each iteration as a way of optimizing the objective function. Each iteration presents two statistical data: the P-factor and the R-factor. The P-factor represents the percentage of observed data covered by the 95PPU, while the R-factor represents the thickness of the 95PPU envelop (Abbaspour, 2015). Abbaspour et al. (2004) and Abbaspour et al. (2007) considered satisfactory values of P-factor to be above 0.7 and R-factor to be below 1.5, although this may vary according to the conditionalities of each model.

The validation comprises running the model with the calibrated parameter intervals in a different period from the one used for the calibration, to check the correlation of the outputs and observed data, and to verify the model performance in uncalibrated periods (Arnold et al., 2012). For both basins used in this study, calibration took place in non-consecutive years, so it excluded the possibility of calibrating in wet periods and validating in dry periods and vice versa.

3. Results and discussion

3.1. Soil physical analysis and infiltration tests

The soil physical analysis showed heterogeneity in relation to its textural classification, ranging from loamy sand to clay loam (**Fig. 5**). Dionizio and Costa (2019) also found a predominant content of sand, ranging between 69% and 85%, while the average clay content varied between 11% and 26%. The sample's heterogeneity in relation to the textural classification demonstrates that, although the soils of Western Bahia usually have low clay contents, there are regions whose soils can present a considerable percentage of clay.

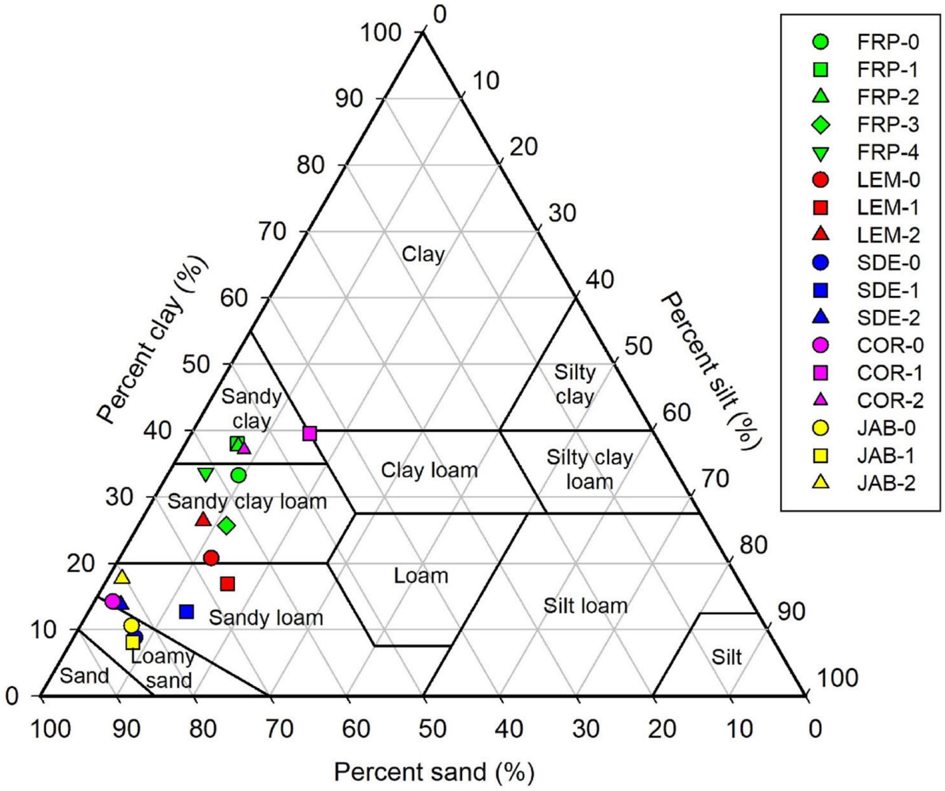

Fig. 5. UAS's Soil Classification chart. The colorful shapes represent the soil samples locations, in *green* - Formosa do Rio Preto (FRP), in *red* - Luís Eduardo Magalhães (LEM), in *blue* - São Desidério (SDE), in *purple* - Correntina (COR), and in *yellow* - Jaborandi (JAB).

In general, Cerrado areas had the highest average macroporosity values, reaching 32% in the JAB-0 area (**Table 4**). Higher macroporosity may be due to the absence of agricultural machinery traffic, larger organic matter content in the soil surface, and presence of numerous roots, when compared to crop areas. On the other hand, the Cerrado areas had the lowest values of average microporosity, reaching 17.4% in the COR-0 area.

The highest total porosity value was observed in FRP-0 area (54.5%), but some cultivated areas also showed high values for this parameter, due to the applied soil management. Among the cultivated areas, it

Table 4 Average steady infiltration rates of the rainy season and dry season, when available.

Test_ID	*Season*	*Average Infiltration Rate [confidence intervals[a]] (mm/h)*	*Average macroporosity (0–45 cm)[confidence intervals[a]] (%)*	*Average microporosity (0–45 cm) [confidence intervals[a]] (%)*	*Average total porosity (0–45 cm) [confidence intervals[a]] (%)*
FRP-0	Rainy	1911.28 [1272.59,2549.96]	24.74 [23.69,25.79]	29.78 [29.02,30.53]	54.52 [53.78,55.27]
FRP-1	Rainy	155.83 [71.08,240.58]	13.02 [11.59,14.45]	34.68 [33.66,35.70]	47.70 [46.46,48.93]
	Dry	135.28 [67.18,203.38]	–	–	–
FRP-2	Rainy	217.52 [44.13,390.92]	9.25 [7.78,10.72]	35.67 [34.56,36.79]	44.92 [43.86,45.98]
	Dry	205.60 [89.82,321.39]	–	–	–
FRP-3	Rainy	–	10.30 [8.98,11.63]	31.62 [30.18,33.07]	41.93 [40.86,42.99]
FRP-4	Rainy	156.72 [86.47,226.97]	10.98 [8.81,13.15]	30.85 [28.64,33.05]	41.82 [39.52,44.13]
LEM-0	Rainy	1204.29 [700.71,1707.86]	14.17 [12.87,15.46]	34.66 [33.20,36.11]	48.82 [47.59,50.06]
LEM-1	Rainy	345.60 [185.76,505.44]	16.13 [13.66,18.61]	28.28 [27.59,28.96]	44.41 [41.79,47.03]
	Dry	260.60 [152.21,368.98]	–	–	–
LEM-2	Rainy	55.13 [24.40,85.86]	9.14 [8.17,10.12]	28.83 [27.61,30.05]	37.97 [36.46,39.49]
	Dry	63.64 [30.76,96.52]	–	–	–
SDE-0	Rainy	721.57 [570.02,873.13]	7.16 [6.33,8.00]	34.45 [33.16,35.74]	41.62 [40.64,42.59]
SDE-1	Rainy	221.26 [135.01,307.51]	10.85 [9.59,12.12]	26.65 [25.53,27.77]	37.50 [36.44,38.57]
	Dry	117.69 [93.13,142.24]	–	–	–
SDE-2	Dry	75.27 [28.11,122.44]	–	–	–
SDE-3	Rainy	32.48 [13.49,51.47]	10.25 [8.81,11.68]	23.40 [21.89,24.90]	33.64 [32.05,35.24]
COR-0	Rainy	896.01 [699.21,1092.80]	22.52 [21.79,23.25]	17.76 [17.42,18.10]	40.28 [39.64,40.92]
COR-1	Rainy	285.08 [163.63,406.54]	13.27 [11.34,15.20]	37.79 [35.91,39.66]	51.06 [50.02,52.10]
	Dry	159.78 [93.80,225.76]	–	–	–
COR-2	Rainy	346.34 [268.93,423.75]	13.56 [11.73,15.39]	36.32 [34.51,38.13]	49.88 [48.57,51.19]
	Dry	226.26 [118.21,334.31]	–	–	–
JAB-0	Rainy	722.33 [573.89,870.77]	32.77 [31.12,34.42]	19.99 [18.69,21.30]	52.77 [52.15,53.38]
JAB-1	Rainy	261.80 [103.04,420.56]	21.89 [19.52,24.26]	24.55 [22.44,26.66]	46.44 [45.53,47.34]
	Dry	212.09 [177.00,247.17]	–	–	–
JAB-2	Rainy	111.01 [65.49,156.54]	5.85 [5.37,6.33]	32.53 [31.36,33.69]	38.37 [37.12,39.63]
	Dry	87.44 [58.43,116.46]	–	–	–

a. The confidence intervals were calculated using the Student's t-distribution, at a confidence level of 95%.

is observed that those whose soil has been mobilized more recently are the ones that present greater total porosity. These values indicates that the crop did not affect considerably the porosity in the region, Dionizio and Costa (2019) observed the soil total porosity presents average of 43% for all samples collected.

The microporosity results did not show a significant relationship with soil management but does do so with the crop rotation used in the area. The highest values are associated with the corn crops, possibly due to the adopted management practice on this culture, as well as with the granulometric characteristics of the more sandy soils of these areas in the analyzed points.

Table 4 illustrates the averages of stable infiltration rates and their confidence intervals obtained in each evaluated area, considering the 208 infiltration tests performed during the dry and rainy seasons. It indicates that Cerrado areas had the highest infiltration rates, regardless of their location, and that the cultivated areas showed different behavior, depending on the management adopted.

The higher values obtained for the rate of stable infiltration for the Cerrado areas can be explained by the high values of macroporosity and the low values of soil density, due to the absence of agriculture practices in these areas. Its lower susceptibility to compaction, associated with greater coverage of the soil, the existence of roots in greater quantity, and the greater amount of decomposing organic material directly influences the quality of the soil, improving its physical characteristics and allowing water from precipitation to infiltrate and to be stored in the soil and underground, supplying the groundwater sources.

Even though, in the areas of effective recharge of the Urucuia Aquifer System, the cultivated soils present stable infiltration rates significantly lower than the Cerrado areas, but their infiltration capacity still higher than the water availability (from precipitation) and does not influence the aquifer recharge.

3.2. Water table fluctuation

The WTF calculation in 19 wells were selected across the two river basins located at UAS - Grande River watershed and Corrente River watershed.

For the Corrente River watershed, the recharge in four wells was estimated along the basin with results varying on average from 4.6% to 51% of the average annual volume precipitated (690.2 mm/year) in the period from December 2015 to December 2019 (**Table 5**). For the Grande River watershed, the recharge estimated in 15 wells along the basin with results varying on average from 8.7% to 51.1% of the average annual volume precipitated from September 2011 to December 2019 and an average monthly recharge of 18 mm/month (Table 5 and **Fig. 6**).

The results indicate that in the UAS region, the aquifer recharge can vary from 88 mm/year to 447 mm/year in the Grande River Basin, and between 33 mm/year and 410 mm/year at the Corrente River Basin. The broad range of recharge values can be explained by the local scale representation of the WTF method, varying between 1 and 100 m^2 (Delin et al., 2007) and by variations in precipitation values, which reduces from West to East, as already observed by Pousa et al.

Table 5 Average recharge for all wells calculated throughout WTF for Grande and Corrente River watersheds.

Monitoring Wells	*UTM E*	*UTM N*	*Basin*	*Lithology*	*Peaks*	*Average Recharge Value (mm/month)*	*Average Recharge /Precipitation (%)*
2900020680	367476	8654685	Grande	Fine Sandstone	4	7.26	14.90%
2900020677	411775	8658229	Grande	Fine Sandstone	3	8.21	11.80%
2900024870	430205	8648417	Grande	Fine Sandstone	5	33.58	42.70%
2900020686	467794	8647530	Grande	Fine Sandstone	4	15.03	21.10%
2900020673	451098	8640289	Grande	Fine Sandstone	3	20.35	24.50%
2900021798	397771	8609184	Grande	Medium Sandstone	2	14.55	15.00%
2900020685	447689	8620777	Grande	Fine Sandstone	3	37.32	51.10%
2900021800	432049	8600986	Grande	Fine Sandstone	4	14.84	18.00%
2900024874	460727	8600124	Grande	Medium Sandstone	2	18.92	34.70%
2900020681	421075	8584774	Grande	Fine Sandstone	3	18.74	27.00%
2900024877	445502	8565448	Grande	Medium Sandstone	3	9.58	10.60%
2900024878	428302	8552721	Grande	Medium Sandstone	6	22.05	35.10%
2900024879	408461	8551710	Grande	Fine Sandstone	3	7.41	8.70%
2900020679	497843	8600036	Grande	Fine Sandstone	7	20.19	27.70%
2900020688	466814	8580900	Grande	Medium Sandstone	7	22.89	28.50%
2900029410	408174	8386812	Corrente	Fine Sandstone	2	34.26	51.00%
2900029481	535619	8534819	Corrente	Fine Sandstone	3	10.15	18.20%
2900029483	550859	8568803	Corrente	Fine Sandstone	3	19.06	26.40%
2900029489	444006	8528148	Corrente	Fine Sandstone	3	2.84	4.60%

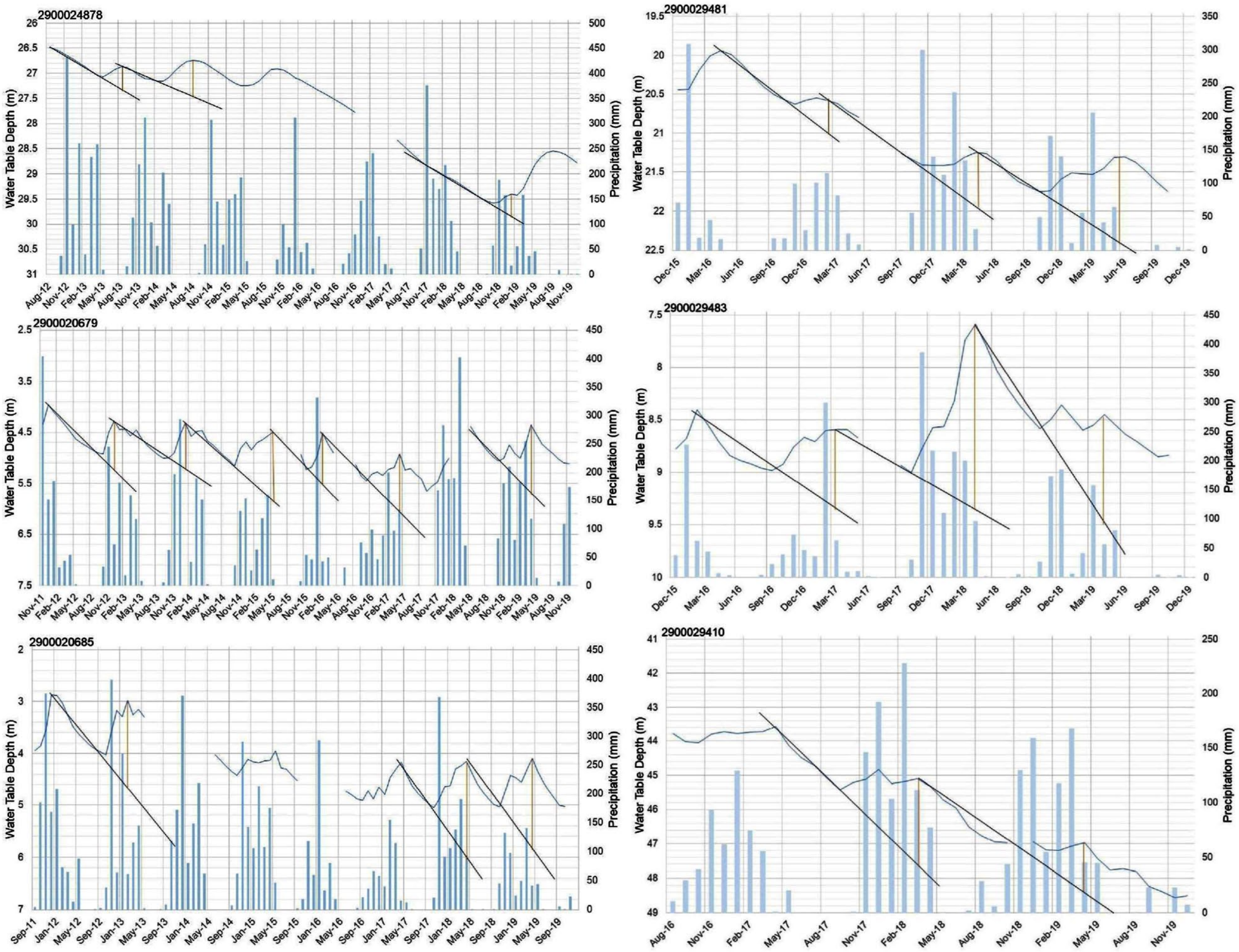

Fig. 6. The image shows some of the selected wells that returned the smallest, intermediate, and highest recharge/precipitation values. On the left are wells in the Upper Grande river watershed, on the right, the wells represented are in the Corrente River watershed.

(2019). The average recharge corresponding to 25% of the precipitation relates to the results found by Albuquerque and Chaves (2011). The authors applied the baseflow separation in the Fêmeas watershed, a subbasin of the Grande River Basin.

3.3. SWAT model simulations

Simulations of two sub-basins were performed in SWAT model, one for Grande River Basin and the second for Corrente/Arrojado River Basin in order to calculate the deep recharge in each watershed.

Table 6 Global Sensitivity Analysis for the calibrated stations in Grande River Basin.

Global sensitivity - SUB 1			*Global sensitivity - SUB 17*		
Parameter Name	*t-Stat*	*p-value*	*Parameter Name*	*t-Stat*	*p-value*
1:R__CN2.mgt	–2.636	0.008	**1:R__CN2.mgt**	0.758	0.449
2:V__ALPHA_BF.gw	–1.991	0.047	**2:V__ALPHA_BF.gw**	–70.467	0.000
3:V__GW_DELAY.gw	0.841	0.400	**3:V__GW_DELAY.gw**	1.928	0.054
4:V__GWQMN.gw	0.611	0.541	**4:V__GWQMN.gw**	–0.147	0.883
5:V__GW_REVAP.gw	2.141	0.032	**5:V__GW_REVAP.gw**	1.803	0.072
6:V__ESCO.hru	–0.230	0.817	**6:V__ESCO.hru**	–4.418	0.000
7:V__EPCO.hru	1.000	0.317	**7:V__EPCO.hru**	–0.689	0.491
8:R__SOL_AWC(..).sol	1.717	0.086	**8:R__SOL_AWC(..).sol**	4.391	0.000
9:R__SOL_K (..).sol	–1.816	0.069	**9:R__SOL_K(..).sol**	2.400	0.017
10:V__REVAPMN.gw	–1.733	0.083	**10:V__REVAPMN.gw**	0.527	0.598
11:V__RCHRG_DP.gw	–4.943	0.000	**11:V__RCHRG_DP.gw**	–3.360	0.001
12:V__SLSOIL.hru	1.582	0.114	**12:V__SLSOIL.hru**	–2.476	0.014
13:V__CANMX.hru	–0.695	0.487	**13:R__SOL_BD(..).sol**	0.084	0.933

Obs.: R: relative change; V: replace value. (Abbaspour, 2015).

Table 6 shows a sensitivity analysis performed for Grande River watershed, for 13 parameters. The most sensitive parameters are identified from a multiple regression system within SWATCUP, comparing the effect of changing parameters with objective function values. In the analysis, t-stat and p-value are generated. The t-stat is the coefficient of the parameter divided by the standard error. The p-value tests the null hypothesis that the coefficient is equal to zero. Thus, a low p-value indicates that you can reject the null hypothesis, with the variable having some effect on the simulation result. The greater the absolute value of t-stat and the smaller the p-value, the more sensitive the parameter (Abbaspour, 2015). For sub-basins 1 and 17 the most sensitive parameters identified were RCHRG_DP and ALPHA_BF. We can also see in Table 6 that the parameters of sub-basin 17 appear to be more sensitive than those of sub-basin 1. This can be explained by the fact that sub-basin 17 is located upstream in the Grande River Basin, so at the time of the sensitivity analysis in sub-basin 1, the entire upstream extension already had been calibrated and validated influencing the hydrological dynamic downstream, requiring minor adjustments in the outlet area.

SOL_AWC: soil available water content (mm H_2O); GW_REVAP: groundwater “revap” coefficient (REVAP – water in the shallow aquifer returning to the root zone in response to a moisture deficit during the time step); ESCO: soil evaporation compensation factor; CN2: runoff curve number for moisture condition II, which is the average of soil moisture between the wilting point and the field capacity; REVAPMN: threshold depth of water in the shallow aquifer for “revap” or percolation to the deep aquifer to occur; EPCO: plant uptake compensation factor; ALPHA_BF: baseflow alpha factor; GW_DELAY: groundwater delay time (days): GWQMN: threshold depth of water in shallow aquifer for return flow to occur; SOL_BD: soil bulk density (g/cm^3); SOL_K: saturated hydraulic conductivity (mm/hr); SLSOIL: Slope length for lateral subsurface flow (m); RCHRG_DP: deep aquifer recharge (Neitsch et al., 2011).

Regarding the statistical parameters of the model evaluation, **Table 7** shows that, for the Grande River Basin, the model shows a very good fit, with satisfactory values in all the statistical parameters of performance analysis, as Moriasi et al. (2007) considers NS values above 0.5 satisfactory and PBIAS values between −10 and +10 very good. Chung et al. (2002) considers R^2 values greater than 0.5 to be satisfactory. Finally, Abbaspour (2015) considers P-factor values above 0.7 and R-factor less than 1.5 to be satisfactory.

Fig. 7 and **Fig. 8** present the graphs with the comparison between the observed flows and the best simulation, in addition to the uncertainty range (95PPU) of the model for the calibrated stations of the Grande River Basin. Overall, the SWAT simulations had a satisfactory performance, identifying the flow trends, but underestimating the flow peaks and occasionally overestimating flow during the dry periods. According to Cho et al. (2009), it may occur because sparse

Table 7 Statistical parameters of model evaluation on Grande River Basin.

		NS	*R^2*	*PBIAS*	*P-factor*	*R-factor*	*Mean_sim (Mean_obs)*	*StdDev_sim (StdDev_obs)*
SITIO GRANDE - SUB 1	Calibration	0.52	0.58	–0.9	0.88	1.3	19.94 (19.76)	6.67 (6.53)
	Validation	0.55	0.59	–1	0.79	1.16	19.98 (19.78)	6.75 (7.08)
CASA REAL - SUB 17	Calibration	0.74	0.74	–0.8	0.86	0.99	9.43 (9.36)	2.64 (3.07)
	Validation	0.63	0.65	–3	0.88	1.14	10.82 (10.5)	2.22 (3.22)

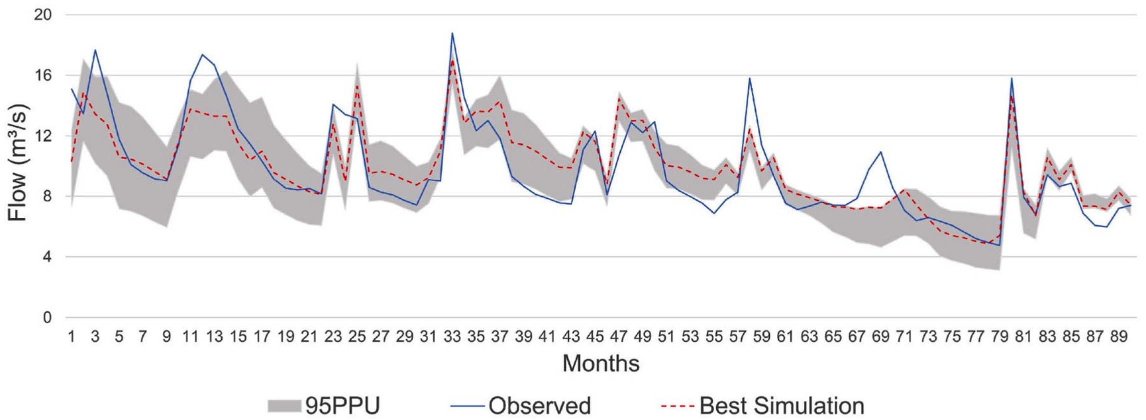

Fig. 7. Simulated and observed flow for SUB 17 (Casa Real station) in the Grande River watershed for a period of 86 months. For this station a NS value of 0.74 in calibration and 0.63 in validation was achieved.

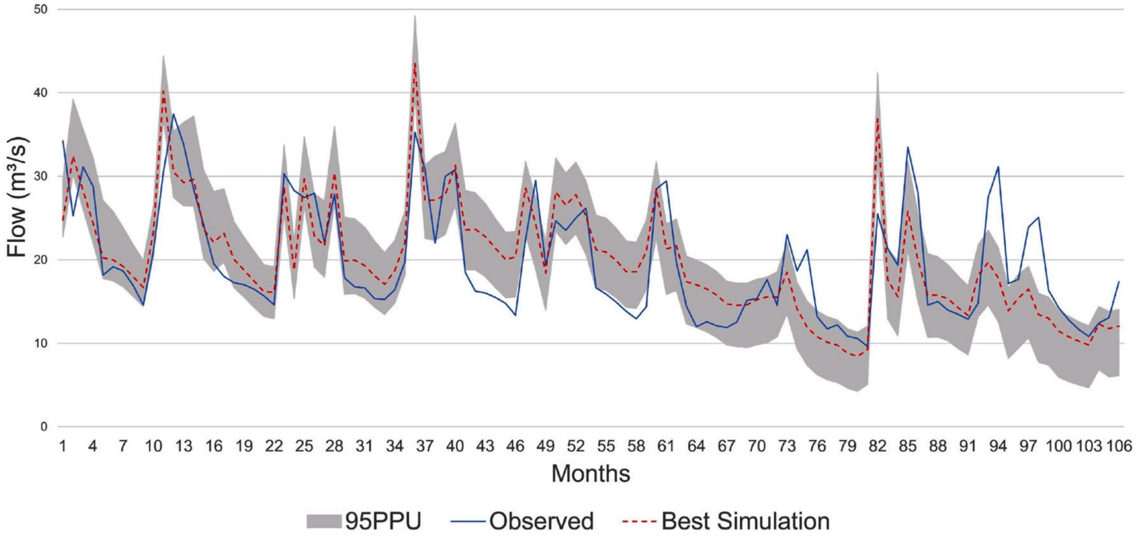

Fig. 8. Simulated and observed flow for SUB 1 (Sítio Grande station) in the Grande River watershed for a period of 106 months. For this station a NS value of 0.52 in calibration and 0.55 in validation was achieved.

spatial distribution and density of rain gauges can result in uncertainties of SWAT output. Additionally, the use of rainfall data extracted from TRMM may corroborate with these results.

Table 8 shows a sensitivity analysis performed for the Corrente-Arrojado River watershed for all the same 13 parameters presented for Grande River analysis. The most sensitive parameters identified for

Table 8 Summary statistics for the evaluation of the Corrente-Arrojado River Basin model.

Global sensitivity - SUB 1			*Global sensitivity - SUB 8*		
Parameter Name	*t-Stat*	*P-Value*	*Parameter Name*	*t-Stat*	*P-Value*
11:R__SOL_K (..).sol	0.035	0.971	**4:V__GWQMN.gw**	0.010	0.991
7:V__REVAPMN.gw	0.229	0.818	**5:R__SOL_AWC(..).sol**	–0.214	0.830
9:V__ESCO.hru	–0.232	0.816	**9:V__GW_REVAP.gw**	–0.457	0.647
3:V__SLSOIL.hru	–0.251	0.801	**8:V__REVAPMN.gw**	–1.244	0.213
4:V__ALPHA_BF.gw	0.332	0.739	**13:V__CANMX.hru**	–1.882	0.060
2:R__CN2.mgt	–0.451	0.651	**3:V__GW_DELAY.gw**	1.986	0.047
13:V__GW_DELAY.gw	0.887	0.375	**6:V__ESCO.hru**	2.445	0.014
1:V__CANMX.hru	1.554	0.120	**1:R__CN2.mgt**	–3.522	0.0005
10:V__EPCO.hru	2.419	0.015	**12:V__SLSOIL.hru**	5.135	4.08E-07
6:V__GW_REVAP.gw	3.462	0.0006	**10:V__RCHRG_DP.gw**	–7.075	0.000
8:V__RCHRG_DP.gw	4.357	1.61E-05	**2:V__ALPHA_BF.gw**	8.885	0.000
5:V__GWQMN.gw	6.169	1.45E-09	**7:V__EPCO.hru**	–10.560	0.000
12:R__SOL_AWC(..).sol	10.159	4.08E-22	**11:R__SOL_K(..).sol**	–11.138	0.000

subbasins 1 and 8 were SOL_AWC and SOL_K. Similar to the Grande River Basin, most of the sensitive parameters in the stations calibrated in Corrente-Arrojado River watershed are related to groundwater and soil physical properties. This is expected, since the river stage behavior of both watersheds are under high influence of the UAS, which contributes with baseflow and the high permeability sandy soils, that are products of the weathering of sandstones from Urucuia Group. Abbaspour et al. (2018), affirms that sensitivity analysis provides information about the most important process-drivers in the study region, according to local characteristics. This corroborates with the results found in the sensitivity analysis performed in this study.

There were more discharge gauges available for the Corrente- Arrojado basin (sub-basin 2 was used for cross-validation), so the upstream station (sub-basin 1) was calibrated, and the downstream station (sub-basin 2) was used for validation of the model, without changing the parameters.

The statistical parameters for the Corrente-Arrojado River model evaluation, shown in **Table 9**, were adequate with satisfactory values in all the statistical parameters of performance analysis, except for subbasin 2 with an NS value of 0.49. Despite this value, it is very close to the value considered satisfactory (0.5) and, in addition, the

Table 9 Summary statistics for the evaluation of the Corrente-Arrojado River model.

		NSE	*R²*	*PBIAS*	*P-factor*	*R-factor*	*Mean_sim (Mean_obs)*	*StdDev_sim (StdDev_obs)*
ARROJADO - SUB 8	Calibration	0.72	0.76	0	0.94	1.31	43.19 (43.20)	9.84 (9.15)
	Validation	0.54	0.69	2.6	0.91	1.45	38.82 (39.86)	10.38 (8.65)
VEREDãO - SUB 1	Calibration	0.56	0.69	0.2	0.92	1.47	16.68 (16.71)	4.13 (3.44)
	Validation	0.68	0.71	0.2	0.96	1.58	16.65 (16.68)	3.56 (3.54)
CORRENTINA - SUB 2	Validation	0.49	0.56	2.1	0.81	1.1	24.77 (25.29)	4.74 (4.72)

model could reproduce 81% of the observed values with an uncertainty range considered adequate. In sub-basins 1 and 8 the model could reproduce more than 90% of the observed values in the flow record, under an acceptable range of uncertainty. Also, the R^2 and PBIAS values achieved are good and very good, respectively, showing a good correlation between the simulated and observed discharge.

Fig. 9 and **Fig. 10** show the graphs with the comparison between the observed flow and the best simulation, in addition to the uncertainty range (95PPU) of the model for the calibration stations of the Corrente- Arrojado Basin. **Fig. 11** presents the results of the cross-validation for sub-basin 2, which shows a lower correlation between

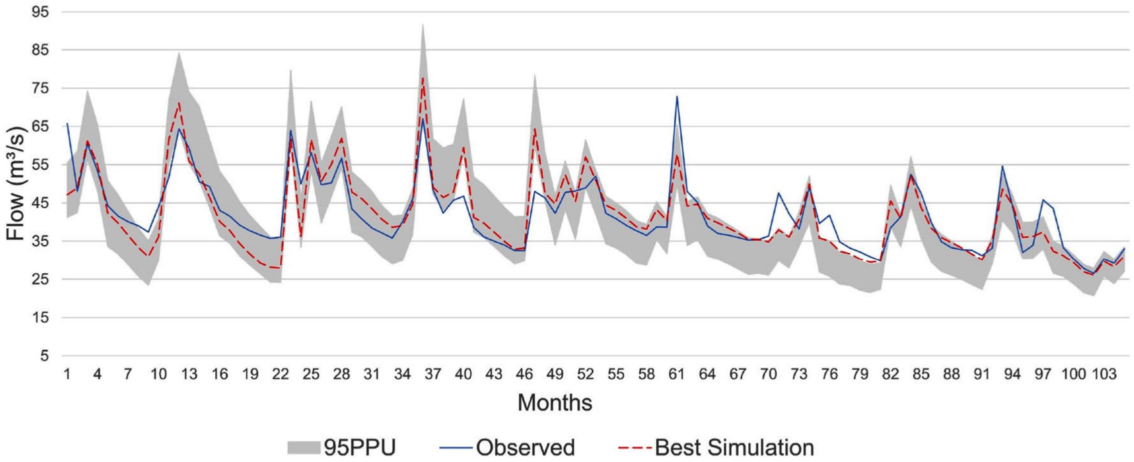

Fig. 9. Simulated and observed flow for SUB 8 (Arrojado station) in the Corrente-Arrojado River watershed for a period of 103 months. For this station a NS value of 0.72 in calibration and 0.54 in validation was achieved.

the observed and simulated parameters. According to Abbaspour et al. (2015), minor inconsistencies are expected in highly managed watersheds with diversity of water use impoundment and management, which is the case of our study area. The station is in the basin's

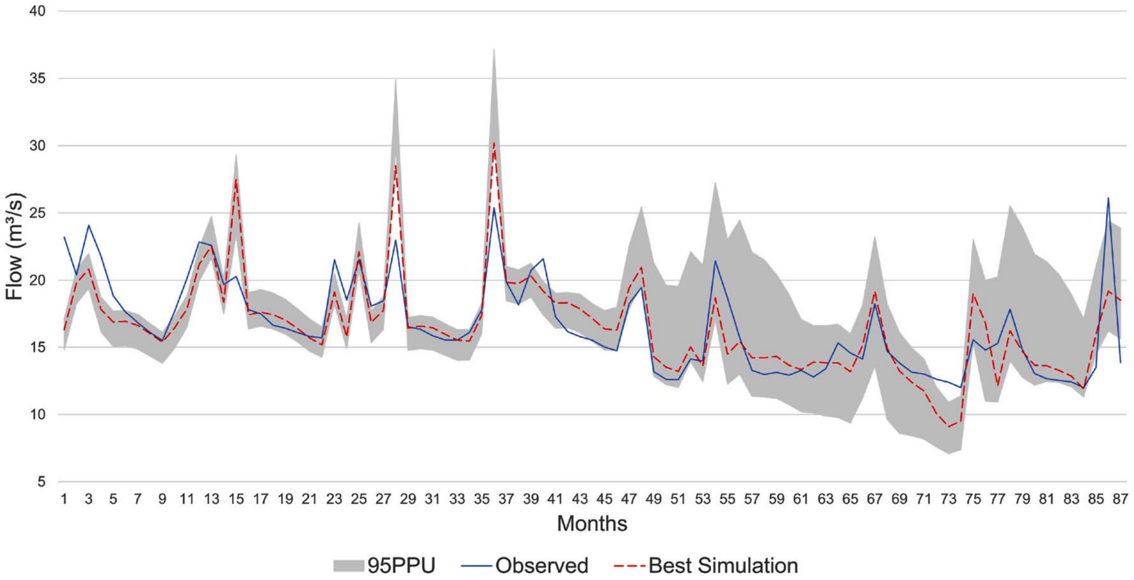

Fig. 10. Simulated and observed flow for SUB 1 (Veredão station) in the Corrente-Arrojado river basin. For this station a NS value of 0.56 in calibration and 0.68 in validation was achieved.

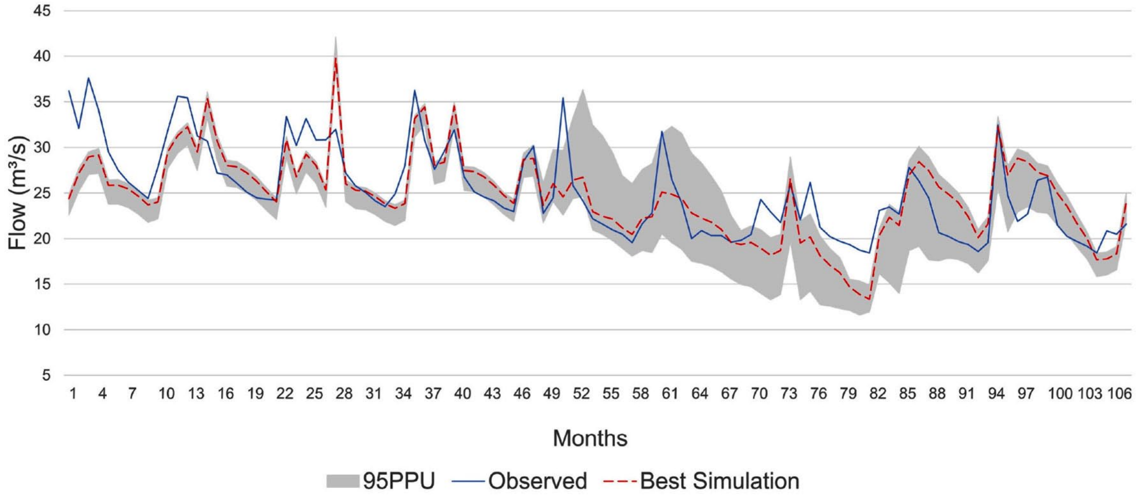

Fig. 11. Graph comparing the range of adjusted values (95PPU), best simulation, and observed flow data in the cross-validation of SUB2 (Correntina station) for a period of 106 months.

outlet; and its historical series brings upstream accumulated uncertainties, such as dams and water extraction, which can change the flow behavior.

As observed for Grande River Basin, the results generated for the base flow on Corrente/Arrojado Rivers for the simulated period also were analyzed in this study and compared with previous studies to provide more evidence to validate the model.

The model generated an average baseflow value of 96% of the total flow for the period from 2011 to 2019. Gaspar (2006) analyzed the baseflow for the entire Corrente River Basin from 1975 to 2005 and obtained an average 93% of the total runoff in that period. In the most recent study by Gonçalves et al. (2018), the authors have calculated the average baseflow for the period from 1977 to 2015 for stations in the region of Corrente and Arrojado rivers and the result was 95% of the total flow. Thus, the model used in the present study has provided an average proportion of the base flow quite similar to the most recent works in the region.

The Grande River watershed estimated average annual recharge was 192 mm for the period from 2011 to 2019, which corresponds to 19% of the average annual precipitated volume in the same period. Regarding the baseflow, the calculated value was 100 mm/year, contributing to 98% of total flow. The baseflow value calculated in SWAT is close to the average annual baseflow value of Grande River Basin estimated by Gonçalves et al. (2018), which was 94%.

Finally, the value of the estimated average annual recharge calculated for the 2011–2019 period in the Corrente-Arrojado River Basin was 295 mm/year, which is equivalent to 29% of the average annual precipitation. This recharge value is significantly large compared to recharge estimated for the Grande River Basin. These results suggest, despite the predominantly homogeneous behavior of UAS, the recharge may vary substantially for different areas of the UAS.

The historical data available for Sítio Grande station (464150000), which is found in the outlet (SUB1) of Grande River watershed, and the rainfall station of the same name from ANA (1245007), are presented on **Fig. 12**. A significant trend of river flow decline, from 40 m^3/s in 1977 to approximately 28 m^3/s in 2019, while no significant reduction of precipitation during this period occurred, according to the rainfall centered moving average.

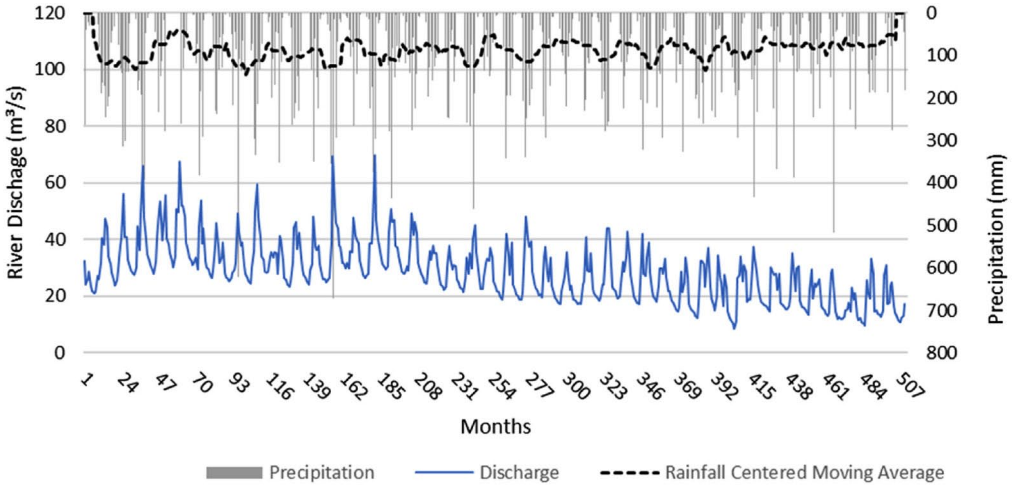

Fig. 12. Sítio Grande River discharge gauge and rain gauge stations time series from 1977 to 2019 indicating a decreasing trend in river flow rate, and with a small trend showing no significant decrease in precipitation volume.

Recent studies have warned about possible influences of the over-exploitation of water resources in lowering the levels of UAS rivers and groundwater table (Gonçalves et al., 2018; Pousa et al., 2019; Marques et al., 2020). Gonçalves et al. (2018) showed a significant drop of 49% in the contribution of the rivers in the basin's areas to the São Francisco River flow. They pointed out that a major cause could be the increasing anthropic use of the region's water resources. Marques et al., (2020) presented the decrease in average annual precipitation in the western region of Bahia in the last decade, combined with the increase in the exploitation of groundwater and surface water, which might have generated a drop in groundwater levels for some areas of the UAS. But these authors suggested that the climatic variation itself does not justify this decrease in the water table level, warning there could be future social tensions in the region if the agricultural expansion continues without adequate management of water resources.

These previous studies - and the current one – suggest that the increasing agricultural exploitation of groundwater in recent decades may have been impacting the baseflow contribution to the studied rivers' discharge in some sub-basins, especially those ones located near the headwaters.

The infiltrometer tests indicated a great discrepancy between the Cerrado (native Brazilian savannah-like vegetation) areas as compared to the crop areas. The values obtained for natural vegetation with the ones from recent crops (opened to 2017/2018 season), the differences in the infiltration rate can vary between 176% and 1127% during the rainy season. Despite this difference, the lower infiltration rate in the cropped areas does not significantly affect infiltration in the shallow portion, with an average of 198 mm/h in the rainy period and 154 mm/h in the dry period, much lower than the maximum values calculated via WTF and SWAT approaches. This result shows that reduction in water availability is not influenced by different soil uses.

The WTF were used to estimate recharge in 19 wells within the Grande and Corrente Rivers Basin. The results revealed that on the UAS area the recharge can range from 88 mm/year to 447 mm/year in the Grande River Basin, and between 33 mm/year and 410 mm/year at the Corrente River Basin. These values represent an average of 24.8% and 25% of total average precipitation, respectively. The simulations performed in two sub-basins of the Grande and Corrente Rivers, by using SWAT method, have estimated the recharge for the Grande and Corrente-Arrojado watersheds, of 192 mm and 295 mm, respectively. These values correspond to 19% and 29% of the average volume precipitated between 2011 and 2019, respectively.

4. Conclusions

The western region of Bahia State is one of the most active expansion areas of irrigated agriculture in Brazil. This has placed a burden over surface and groundwater resources of the region. In recent years, some conflicts over water use have occurred in the region, which highlights the importance of adequate knowledge of local water resources combined with appropriate management.

We estimated aquifer recharge using several new data sets of the recharge estimates calculated by two different methods - WTF method and by SWAT simulation. Additionally, double-ring infiltrometer tests were performed to evaluate the infiltration rates in different land uses and covers, to analyze the effects of the agriculture in the infiltration and subsequent recharge. Recharge cannot be directly measured from infiltrometer tests, but they provide insights on soil hydraulic conductivity, infiltration rates and their influencing factors. For instance, *in-situ* infiltration tests indicate that land use affects infiltration rates. However, these values, even for the lower estimated infiltration rates, are higher than the rainfall events, which indicate that infiltration capacity has been not compromised in the area. So, there is no significant influence of land use on the recharge of the studied UAS areas.

WTF method results indicate an average recharge value of 24% of precipitation for Grande River watershed, and 25% for Corrente River watershed. These values are close to the ones attained by other studies in the region. The simulations with the SWAT code provided a good result with the rates measured by the gauges system, indicating the flow rate trends. However, the simulations underestimated the groundwater flow rate, especially during the high flow period. The application of remote sense data to complement the precipitation data set could explain it. The recharge values calculated correspond to 19% of the average annual precipitated volume for the period from 2011 to 2019 in the Grande River Basin. In the Corrente-Arrojado River Basin it was equivalent to 29% of the average annual precipitation, in the same period.

Based on these results, the recharge values estimated by the SWAT modeling are very similar to those estimated by using the WTF method and are in line with data from other works from the literature. Therefore, accurate annual recharge rates can be estimated for UAS by using both methods used in this study and our results validate the average recharge percentages in the region.

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