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Papers

Performance of the SEBAL algorithm in estimating flow in watersheds in the Brazilian Savanna

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Radiation balance.
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Abstract
Studies of the variables making up the radiation balanceare essential in climatology, mainly to understand the dynamics of the hydrologic cycle. Decreases in rainfall can be linked to changes in actual evapotranspiration values on the surface, since changes in land use modify the albedo, the vegetation index, and the surface temperature.. The objective of the present study was to evaluate the performance of the Surface Energy Balance Algorithm for Land algorithm in estimating the annual flow in watersheds located in the Brazilian savanna, considered as the simplified result of subtracting the values of rainfall from actual evapotranspiration. The algorithm allows estimation of flows for watersheds that do not have monitoring points, contributing to studies of water availability in large regions that are difficult to access. The results showed a correlation coefficient of 0.99 and a coefficient of determination of 0.99 between annual flows estimated according to categories of use and coverage of land and flows observed at fluviometric stations, with a performance of 99%, indicating the applicability of the model to estimate flows in areas without monitoring points. For the monthly flows estimated from information recorded by INMET automatic stations, there is a considerable effect of seasonality, with a record of negative values in the dry period. Despite this, the estimated flows showed a correlation of 0.80 with the observed values, with a performance of 89%. On average, flows in the studied watersheds account for 20% of total rainfall volume, which is an underestimate in comparison with values measured in the field, with an average error of -0.5898 $m^3/s/m^2$.

INTRODUCTION

The study of the variables making up the energy balance, as well as the values derived from heat flow and evapotranspiration, are fundamental to understanding the dynamics of the hydrologic cycle. These projections make it possible to carry out activities such as planning irrigation, estimating the need to replenish water in the soil, and developing studies of subsurface water recharge, in addition to allowing researchers to understand climate and environmental changes.

The uncontrolled growth of urban centers and intense industrial activity directly contribute to the aggravation of the water crisis. However, agricultural practices are the origin of the greatest pressure on water resources that directly affects water production and supply. Abrupt changes in the relationships of land use and land

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cover, especially those related to forest removal, and uncontrolled occupation of valley floors and aquifer recharge areas, among other factors, directly impact the hydrologic cycle, reducing the system's capacity to "produce" water and, consequently, the supply of this resource (REBOUÇAS, 1997; MARTINS; GOMES FILHO, 2013; CUNHA; ALVALÁ; OLIVEIRA, 2013).

Reductions in rainfall may be directly related to changes in values of actual surface evapotranspiration, given that changes in land use, such as the conversion of forests into pastures, modify the albedo, the vegetation index, and surface temperatures, which are biophysical parameters essential to the radiation balance and, consequently, to the definition of heat flow and evapotranspiration (CUNHA, ALVALÁ; OLIVEIRA, 2013). Studies addressing the effects of environmental changes on energy flow on the surface are fundamental to water resource conservation and, therefore, to life on Earth.

The Brazilian savanna, popularly known as "the father of waters," encompasses a considerable share of the headwaters that originate the main watersheds in the country (those whose central elements are the Paraná, São Francisco, Araguaia, and Tocantins Rivers, among others). It is the second-largest Brazilian morphoclimatic zone, it occupies over two million square kilometers (approximately 24% of the country's territory), and it has been in advanced degradation conditions since the mid-20th century. Klink and Machado (2005) emphasized that, despite its great biodiversity, only 2.2% of the Brazilian savanna was protected in full protection areas, and 1.9% was included in sustainable use units, whereas indigenous lands accounted for 4.1% of its area.

Machado et al. (2004) stressed that the average annual loss of the Brazilian savanna area between 1985 and 1993 was 1.5%, decreasing to 0.67% from 1993 to 2002, with an estimated annual deforestation rate of 1.1%. These authors predicted that, if this rate was maintained, it was expected that the Brazilian savanna would disappear by 2030. Subsequent studies, such as that carried out by Rocha et al. (2011), have pointed to deforestation of 366,100 hectares between 2002 and 2009, with 47% of the warnings concentrated in the states of Mato Grosso and Bahia. This indicates that the expansion of the agricultural frontier in the Brazilian savanna continues, especially on the border between the states of Goiás and Mato Grosso, in the interface between the Brazilian savanna and the Amazon, and in the region known as MaToPiBa, located on the borders of the states of Maranhão, Tocantins, Piauí, and Bahia. According to data provided in 2019 by the PRODES project, developed by the Brazilian National Institute for Space Research, the Brazilian savanna showed deforestation that was 35% higher than that observed in the Amazon between 2008 and 2019. All the states had progressive reductions in Brazilian savanna areas, with Mato Grosso, Goiás, and Minas Gerais standing out.

Therefore, it is fundamental to design studies that can provide resources for public policies and action plans oriented toward recovering Brazilian savanna areas and "water production" in watersheds. Among these actions is the creation of conservation units, restoration of low-albedo vegetation, increased surface roughness, favoring retention and infiltration of rainwater, decreased runoff, among others. Lima (2010) noted that "water production" refers to a watershed's total discharge over a certain period (Q), which can be defined in a simplified form as the rainfall (R) fraction that does not go back into the cycle as evapotranspiration (ET) (Q = R – ET).

These actions help "control" evapotranspiration and guarantee flow regularization, especially in areas with marked seasonality and long dry periods such as the Brazilian savanna. Currently, there is a variety of techniques to measure these water "production and loss" relationships in the environment. Specifically on the surface, the Brazilian National Water Agency (ANA, as per its acronym in Portuguese) maintains a rain and flow observation network that covers a good share of the Brazilian territory. Additionally, there are monitoring stations maintained by state agencies, nongovernmental organizations, and energy production companies. The Brazilian National Meteorology Institute (INMET, as per its acronym in Portuguese) has a station network that provides, not only pluviometric data, but also temperature, humidity, wind, and pressure information that allows calculation of evapotranspiration by applying different methods and models.

Among the several climate and hydrologic models used to estimate evapotranspiration, such as the Soil-Vegetation-Atmosphere Transfer Model and the Mapping Evapotranspiration at High Resolution with Internalized Calibration Model, the authors of the present study opted to apply the Surface Energy Balance Algorithm for Land (SEBAL), mainly because of the extent of the study area, the lack of climatological data, and the ease of dealing with the model, which requires little field information to provide an estimate of evapotranspiration (PEREIRA; SEDIYAMA;

VILLA NOVA, 2013; MARTINS, 2015; ALVES, 2019).

The Surface Energy Balance Algorithm for Land, developed by Bastiaanssen (1995), is one of the most complete models for studying surface heat flow by using satellite imagery and climatological information, including air temperature and wind speed. It is basically mathematical and mostly free of assumptions, which decreases the margin of error in its validation. Liou and Kar (2014) observed that SEBAL was designed to calculate the components that make up the energy balance locally and regionally, from limited surface data, by using empirical relationships and physical parametrization. Precision ranging from 85% to 95% in daily and seasonal field scales was found, in more than 30 countries, under several climatic conditions.

According to Bastiaanssen (1995), the main incentive to design SEBAL was the need to overcome problems shown by some algorithms when estimating surface flow using remote sensing imagery. In another study, Bastiaanssen et al. (1998) mentioned that the main issues found with SEBAL were related to the fact that the data used is instantaneous, which makes daily and seasonal estimates relatively inadequate for more detailed scales.

SEBAL has been used by many researchers worldwide to examine varied agricultural systems. In addition to studies by Bastiaanssen (1995; 2000) and Bastiaanssen et al. (1998), others that have addressed this subject have stood out in the literature, including those by Allen et al. (2002), Ahmad and Bastiaanssen (2003), Ayenew (2003), Hemakumara et al. (2003), Tasumi et al. (2005), Giacomoni (2008), Bezerra (2008), Kongo and Jewitt (2006), Kimura et al. (2007), Mendonça (2007), Nicácio (2008), Gomes (2009), Li and Whenzi (2010), Sun et al. (2011), Ruhoff (2011), Martins (2015) and Freitas (2018).

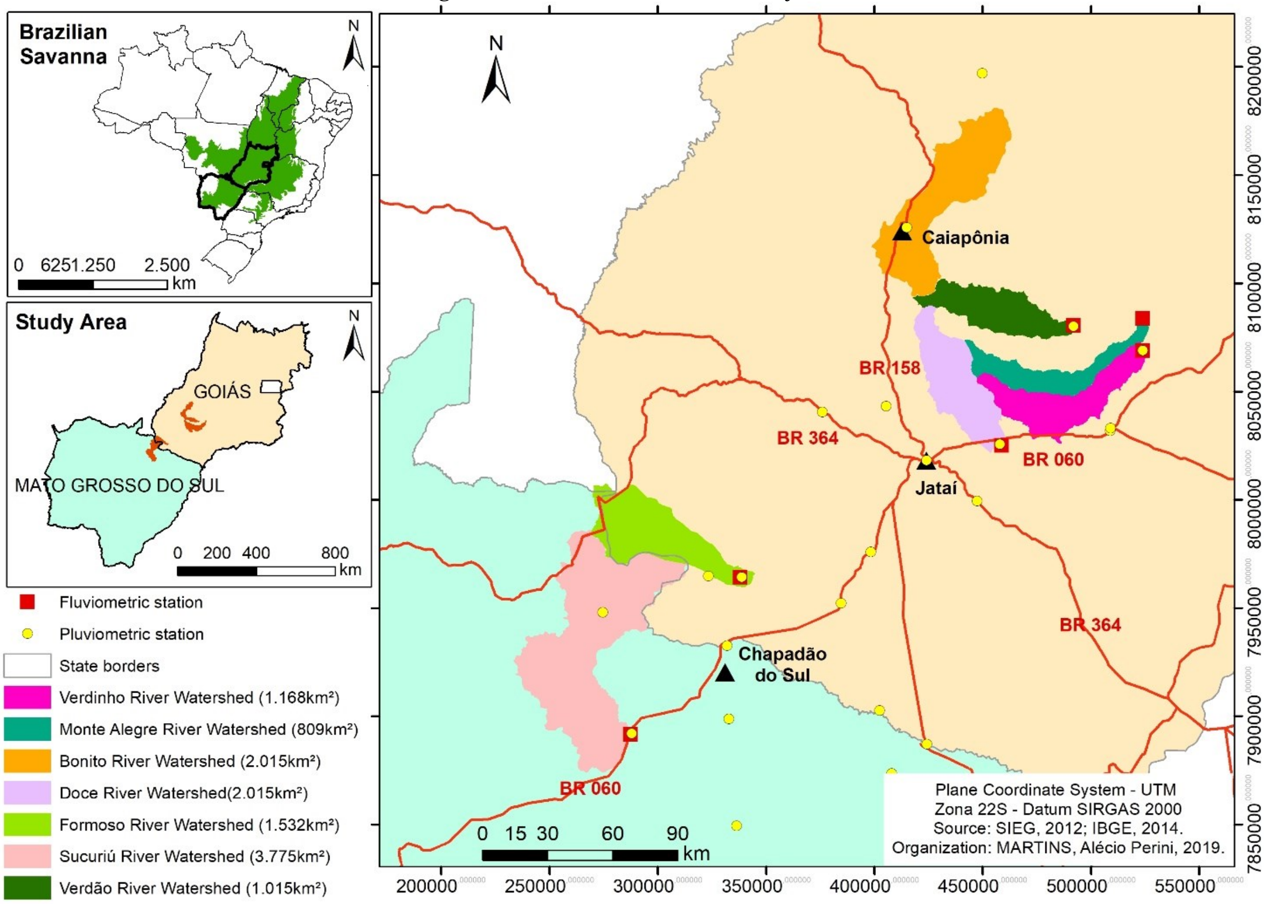
The objective of the present study was to evaluate the performance of SEBAL in calculating actual evapotranspiration and, by applying a simplified water balance, in estimating annual flow in watersheds in the Brazilian savanna region. By doing that, the present study aimed to provide a method for estimating flow in watersheds that do not have monitoring stations, contributing to research on water availability in large areas or those that are difficult to access.

STUDY SETTING

Taking into account the diversity of landscapes in the examined region, seven watersheds or parts of watersheds were selected in locations with similar climatic characteristics (Figure 1). They were: a) the Formoso River watershed, with an area of 1,532 km², located in the southwestern end of the state of Goiás and with over 40% of its territory turned into Emas National Park; b) the upper course of the Sucuriú River watershed, with an area of 3,775 km², located in the northeast region of the state of Mato Grosso do Sul, showing a variety of agricultural uses; c) the upper and middle courses of the Doce (2,015 km²), Monte Alegre (809 km²), Verdão (1,015 km²), and Verdinho (1,668 km²) rivers, between the municipalities of Jataí, Rio Verde, and Montividiu, in the southwest region of the state of Goiás, also having a considerable diversity of agricultural uses, including sugar cane cultivation and center-pivot-based irrigation, in addition to reduced areas with remaining natural vegetation; and d) the Bonito River watershed, with an area of 2,015 km², located in the municipalities of Caiapônia, Palestina de Goiás, and Arenópolis, in a region where the agricultural frontier of the state of Goiás is currently being expanded.

One of the main characteristics of the study area is its flat and slightly undulating topography, which was fundamental for the southwest region of Goiás becoming a focus for implementation of federal agricultural development programs in the 1970s and 1980s. Martins et al. (2016) summarized the region's landscape as being made up of two distinct units: flat plateaus, with flat relief sculpted in basalt and covered by sandstone and tertiary sediments that originate oxisols; and depressions and valleys, with relief ranging from slightly undulating to undulating and the presence of older sandstones and sandy texture soils, originally covered with different types of Brazilian savanna.

Figure 1 - Location of the study area.



Source: SIEG, 2012; IBGE, 2014. . Organization: MARTINS, 2019.

According to the Köppen classification, the region has an Aw climate, with over 85% of the rainfall concentrated in the months from October to April, and a marked dry season from May to September, with pronounced seasonality (MARIANO, 2005).

PROCEDURES

Databases and implementation of SEBAL to estimate evapotranspiration

Initially, three INMET weather stations were identified in the region to calibrate and validate the model: those located in Jataí, Caiapônia (both in Goiás), and Chapadão do Sul (in Mato Grosso do Sul). The types of information necessary to calibrate the model are: average, maximum, and minimum air temperature (ºC); maximum and minimum relative air humidity (%); atmospheric pressure (hPa); wind speed (m/s); rainfall (mm); and radiation (W/m²).

The study was designed for the hydrologic year between 10/01/2018 and 09/30/2019 based on rainfall and flow data obtained at ANA pluviometric and fluviometric stations located in the municipalities of Jataí, Rio Verde, Montividiu, Caiapônia, Arenópolis, Serranópolis, Aporé, and Chapadão do Céu (Goiás), and Chapadão do Sul, Cassilândia, and Costa Rica (Mato Grosso do Sul). The image bank was composed of satellite imagery (Landsat 8, Operational Land Imagers [OLI] and Thermal Infrared Sensors [TIRS]) and radar imagery (Shuttle Radar Topography Mission [SRTM]), and all the images had 30 m spatial resolution. Satellite imagery was obtained by the OLI (bands 2, 3, 4, 5, 6, 7, and 8) and TIRS (band 10) Landsat 8 sensors free of charge after registration on the United States Geological Survey website.

The study was developed with ArcGIS 10.6.1® software, licensed for use at the Geoinformation Laboratory at the Federal University of Goiás/Jataí Campus, mostly by using the Raster Calculator. First, the radiometric correction for each band was carried out based on radiance and reflectance calculations, as described by Ariza (2013). The calculations related to radiation incidence angle, Earth-Sun distance, exo-atmospheric solar radiation, corrected reflectance, and atmospheric transmissivity followed the parameters of the Mapping Evapotranspiration at High Resolution with Internalized Calibration Model described by Allen et al. (2007).

Correlations between the estimated and observed flows were identified, and for those with correlation values higher than 0.7 (strong correlation), regression equations, mean error, and squared error were obtained, and performance tests involving the D and C indexes were carried out. Both of them showed a performance scale ranging from very poor to great, according to Oliveira (2016): very poor: < 0.40; poor: from 0.40 to 0.50; acceptable: 0.50 to 0.60; regular: 0.60 to 0.65; good: 0.65 to 0.70; very good: 0.75 to 0.85; and great: > 0.85. The performance measured by the D index is related to the difference between predicted and observed values (WILLMOTT et al., 1985), whereas the C index indicates the method reliability and/or performance and is calculated by multiplying the Pearson's correlation coefficient by the D index (CAMARGO; SENTELHAS, 1997).

The implementation of SEBAL followed the procedures described by Allen et al. (2002) and updated according to the results of studies carried out by Ahmad and Bastiaanssen (2003), Ayenew (2003), Tasumi et al. (2005), Bezerra (2006), Kongo and Jewitt (2006), Kimura et al. (2007), Mendonça (2007), Nicácio (2008) and Martins (2016).

The calculation of reference evapotranspiration was performed by using the Penman–Monteith equation described by Allen et al. (1998) in the Food and Agriculture Organization of the United Nations Irrigation and Drainage Paper no. 56. The instant actual evapotranspiration (ETh) was calculated pixel by pixel, considering both ideal and water saturation or restriction conditions, from the latent heat outcome (λET) and the latent heat of vaporization (λ), according to equations 1 and 2 described by Allen et al. (2007).

$$ETh = 3{,}600 * \lambda ET/\lambda \quad (1)$$

where λ is the latent heat of vaporization (defined in equation 2 and expressed in J/kg), which is calculated from the surface temperature (Ts). The factor 3,600 is necessary to convert minutes into hours (BASTIAANSSEN et al., 1998; NICÁCIO, 2008).

$$\lambda = [2.501 - 0.00236 * (Ts - 273.16)] * 10^6 \quad (2)$$

To estimate the daily (equation 3) and monthly/seasonal (equation 4) evapotranspiration, it is necessary to calculate the reference values (ETo) for 24 hours and for the period, in addition to obtaining a component known as the evaporative fraction (ETrF), which is defined as the ratio between instant evapotranspiration (ETh) and reference evapotranspiration (ETo). According to Allen et al. (2002), the values of the evaporative fraction are similar to the crop coefficient (Kc), ranging from 0 to 1, and occasionally reaching values higher than 1 when ETh is considerably higher than ETo, such as for bodies of water and areas with dense arboreal vegetation.

$$ET24 = ETrF * ETo24 \quad (3)$$

where ETo24 (mm/day) is the ETo accumulated over 24 hours on the day the image is obtained, calculated as the sum of the hourly ETo values recorded over the day.

$$ETperiod = ETrFperiod * \sum_1^n ETo24 \quad (4)$$

According to Allen et al. (2002), SEBAL calculates the daily evapotranspiration, assuming that the instant ETrF is equal to the 24-hour average value.

Land use and land cover mapping and annual flow estimate

To map the categories of land use and land cover, two OLI/Landsat 8 images with no cloud cover were selected for each of the orbit points used in the present study: a) for orbit point 223/72: images obtained on 02/02/2019 (summer) and 06/26/2019 (winter); b) for orbit point 224/73: images obtained on 01/08/2019 (summer) and 07/19/2019 (winter). Images obtained in different periods are necessary because of seasonality in the region, and crop types must be identified (grains, sugarcane, and irrigated areas).

Initially, colored composition was produced, considering OLI/Landsat 8 bands 2, 3, 4, 5, 6, and 7, with posterior fusion with band 8 (panchromatic, with 15 m spatial resolution) to obtain a colored image with resolution resampled to 15 m. Although the images had already undergone georeferencing, the procedure was applied again and corrected by using highway and drainage networks, both at a 1:100,000 scale, made available by the Brazilian Institute of Geography and Statistics. Satellite imagery was obtained free of charge on the United States Geological Survey/Earth Explorer website and processed by using ArcGIS 10.6.1® software, which is licensed for use at the Geoinformation

Laboratory at the Federal University of Goiás/Jataí Campus.

The classification of the images was carried out under supervision, with the creation of 50 samples for each of the following categories: a) agriculture (sugarcane); b) agriculture (grains); c) irrigated agriculture; d) water; e) wet areas; f) savanna; g) *cerradão*/forest formations; h) pasture; i) degraded pasture; j) forest; k) bare soil/urban areas/paved roads. The Interactive Supervised Classification tool, available in the Image Classification toolbar, was applied. Last, the thematic images were converted into polygon format and submitted to manual error editing and kappa validation, using points selected on the Google Earth Pro app as a starting point, with an accuracy level of 90%.

The map of land use and land cover was converted into the Raster format and the areas of the seven watersheds were cut out. The points used for kappa validation were cross-checked with the variables obtained in the different steps of the SEBAL implementation by using the tool Zonal Statistics as Table, which calculated mean, maximum, and minimum values and standard deviations for each group of samples.

Flow (Q) estimation was carried out by applying the formula Q = R – ET, where R is (monthly and annual) average rainfall in the watershed, measured at the ANA pluviometric stations, and ET is monthly evapotranspiration estimated by applying SEBAL and using remote sensing products. For evapotranspiration, we considered the estimated monthly value for the pixel of the INMET automatic weather station, which was used to calculate reference evapotranspiration (ETo) and monthly value by using the evapotranspiration value for each land use and land cover category.

The calculation of annual flow, which took into account the land use and land cover categories, was carried out according to the following steps: a) calculation of the area of each land use and land cover category in m²; b) estimate of the annual evapotranspiration in each land use category in mm/year; c) calculation of the annual average rainfall in the watershed in mm/year; d) subtraction of the evapotranspiration values from the total rainfall, with the result designated as the flow (in mm/year) for each land use and land cover category; e) multiplication of the flow values by the area of each land use category, with the results expressed in mm/year*m²; f) conversion of the values obtained in the previous step into m³/year/m²; g) conversion of the values calculated in the previous step into daily data, hourly data, and values expressed in m³/second/m².

When summed, the values of flow per second per area of each land use and land cover category express the watershed flow over one hydrologic year, which began on 10/01/2018 and ended on 09/30/2019 in the present study. The results were compared with the data collected at ANA fluviometric stations for checking purposes and submitted to statistical analysis.

RESULTS AND DISCUSSION

As shown in Table 1, the flows estimated by using simplified water balance (R - ETr) were approximately 20% of the rainfall volume over the 2018/2019 hydrologic year, adopted as a standard year for showing values close to the average rainfall records in the region. In the Formoso and Sucuriú River watersheds, the rainfall was slightly higher than the average for the region because of the high values recorded in November 2018.

Table 1. Variables measured at INMET weather stations and ANA fluviometric and pluviometric stations, considering the land use and land cover categories – 2019*.

Variables/Watersheds	Formoso	Doce	Sucuriú	Verdão	Monte Alegre	Verdinho
Average temperature (°C)	23.2	23.0	23.2	23.0	23.0	23.0
Rainfall (mm)	1,897.5	1,641.2	1,897.5	1,620.3	1,497.2	1,541.0
ETo (mm)	2,096.9	2,000.9	2,096.9	2,049.5	2,049.5	2,049.0
ETr (mm)	1,480.3	1,316.4	1,361.6	1,334.1	1,230.2	1,223.0
R-ETr (mm)	402.8	324.8	441.0	286.2	267.0	318.2
R-ETr/P percentage (%)	21.2	19.8	23.2	17.7	17.8	20.6
Area (km²)	1,532.0	2,015.0	3,775.0	1,015.0	809.0	1,168.0
Estimated Q – season (m³/s/m²)	21.4	21.3	27.2	9.2	7.2	11.6
Estimated Q – use (m³/s/m²)	23.6	21.1	78.0	12.7	10.9	15.9
Observed Q – ANA (m³/s/m²)	24.9	23.8	74.7	14.2	11.5	16.6

This table does not show information about Bonito River because it does not have fluviometric monitoring stations. Organization: Prepared by the authors, 2019.

The estimated gross annual flow values obtained by taking into account the land use and land cover categories are similar to those registered at ANA pluviometric stations but differ considerably from those estimated at the automatic INMET station. This happens because of the marked seasonality of the Brazilian savanna, which has a dry season between May and September. In this period, the estimated flow values were negative (Figure 2) at the INMET station, which indicates a water deficit.

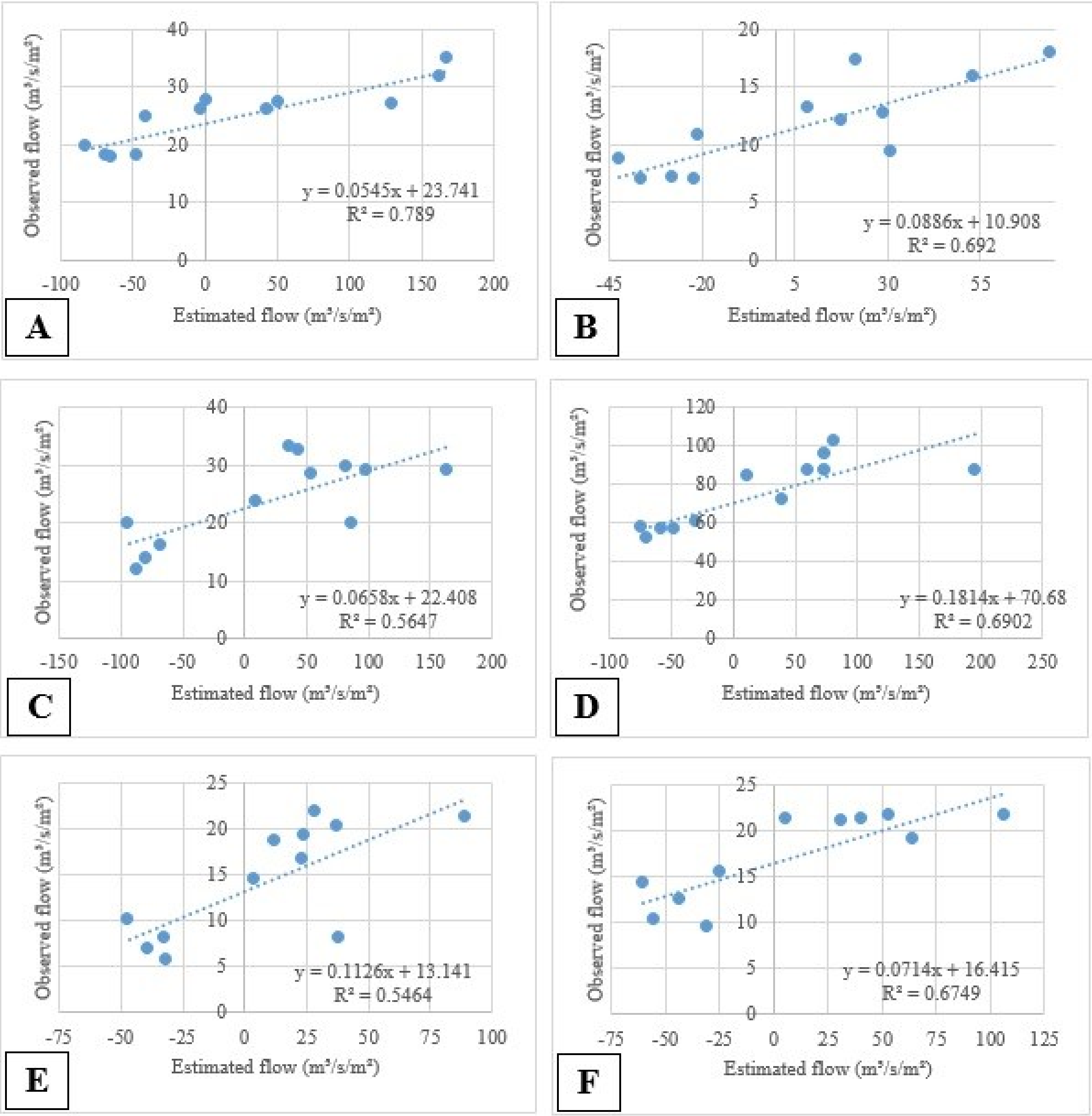
The flows estimated considering the land use and land cover categories showed a very strong correlation with the data recorded at ANA fluviometric stations, with a Pearson's correlation coefficient of 0.9991 and a coefficient of determination of 0.9969, which indicates that the model is nearly 100% accurate (Table 2 and Figure 3). Comparison of the observed data and the estimated flow considering the INMET automatic stations showed that the correlation was 0.8099 and the coefficient of determination was 0.6556, which demonstrates, , the effect of seasonality on the estimated efficiency (Figure 2).

The mean squared error (MSE) and its root were calculated after analysis of the correlation between the variables. These parameters are important indicators of agreement between variables (WILLMOTT et al., 1985). The lower the MSE, the higher the agreement. An MSE of -0.5898 m³/s/m² was identified between observed and estimated flows, indicating an underestimation of the method. In an ideal situation, the MSE should be close to 0 (OLIVEIRA, 2016).

The flows estimated based on the land use and land cover categories showed a D index of 0.9998 and a C index of 0.9989, which indicated excellent performance of SEBAL in estimating the annual flow by using the simplified water balance. For the estimate carried out by using the data collected at INMET automatic stations, the performance indexes were considered excellent (D index equal to 0.8943) and good (C index equal to 0.7243). Although the algorithm extrapolates the values, especially over the dry period, it also showed satisfactory performance in estimating evapotranspiration from monthly data.

Once the proposal to estimate flows based on land use and land cover was validated, the methodology was applied to the Bonito River watershed, a tributary of the Araguaia River watershed, located in the municipalities of Caiapônia, Palestina de Goiás, and Arenópolis, and with an area of approximately 2,015 km². The rainfall recorded from 10/01/2018 to 09/30/2019 was 1,519.1 mm, which is close to the average value in the region. The calculated ETo was 2,000.9 mm, with the ETr corresponding to 70% of this volume (1,378.3 mm). Taking into account the land use and land cover categories, an ETr equal to 1,175.9 mm was calculated.

Figure 2 - Dispersion diagrams showing the relationship between observed flow and estimated flow considering the measurements obtained at INMET automatic stations, 2018/2019 hydrologic year. The figure shows data on the Formoso (A), Monte Alegre (B), Doce (C), Sucuriú (D), Verdão (E), and Verdinho (F) River watersheds.



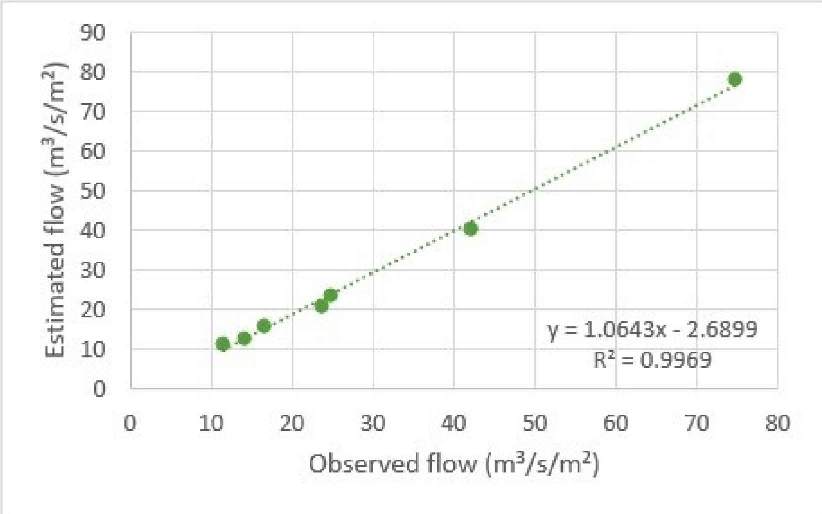
Source: INMET, 2019; ANA, 2019. Organization: Carried out by the authors, 2019.

Table 2. Validation statistics for reference and estimated parameters in the 2018/2019 hydrologic year.

Variables	R	R²	MSE	RMSE	D Index	C Index
Flow estimated based on land use X Flow recorded at ANA stations	0.9991	0.9969	-0.5898	1.4476	0.9998	0.9989
Flow estimated at INMET stations X Flow recorded at ANA stations	0.8099	0.6556	-11.2448	27.5994	0.8943	0.7243

R = Pearson's correlation coefficient; R² = coefficient of determination; MSE = mean squared error; RMSE = MSE square root; D Index = Willmott's performance index; C Index = Camargo and Sentelhas' performance index. Organization: Prepared by the authors, 2019.

Figure 3 - Regression analysis for estimated flow vs. observed flow considering the land use and land cover categories in the 2018/2019 hydrologic year.



Organization: Carried out by the authors, 2019.

By using the monthly and annual R-ETr as input values, an average annual flow of 9.25 m³/s/m² was estimated, ranging from 226.7 m³/s/m² in March to -95.2 m³/s/m² in August, demonstrating the effect of seasonality on monthly estimates. The values estimated based on the land use and land cover categories, which showed a correlation coefficient of 0.9991 with data recorded for watersheds that had field monitoring, resulted in an estimated annual flow of 21.85 m³/s/m², a result that was close to the real values for the Doce River watershed, which has a similar area and showed similar rainfall values in the examined period.

FINAL CONSIDERATIONS

The values calculated for the performance indexes showed that SEBAL is suitable for estimating the annual flow based on remote sensing products by considering the land use and land cover categories and applying the simplified water balance. When monthly estimates for values recorded at INMET automatic weather stations were considered, it was noted that, despite the strong correlation with the observed flows, the performance could be considered good for annual flows, but showed considerable average errors caused by the seasonality of the Brazilian savanna. The dry period, which spans over five months, leads to substantial water deficit values.

Although more tests must be carried out, it is possible to note, based on the regression equation, that the estimated values will probably follow the same patterns as the observed values, which confirms the validity of the application of the algorithm in watersheds that do not have flow monitoring stations.

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