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VALIDATION OF A HYBRID EVAPOTRANSPIRATION MODEL USING SATELLITE IMAGERY AND PRECIPITATION-FLOW DATA

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1 ABSTRACT

To quantify the water balance in watersheds, it is necessary to know the components of the hydrologic cycle, especially evapotranspiration (ET). Many studies have been conducted using a single-source model such as SEBAL to estimate the actual ET (ETa) from satellite imagery; however, other models have been developed and continuously improved, such as the Two Source Energy Balance (TSEB). This study evaluated ETa estimation performed by a hybrid TSEB ET model programmed in the Spatial Evapotranspiration Modeling Interface (SETMI) using satellite imagery. The evaluation was conducted over two full hydrological years, developing a new methodology to convert hourly ETa data to monthly and annual data. The results of applying the TSEB/SETMI model to Landsat 8 imagery were validated to a water balance calculation from field measurements in three representative watersheds in Corumbataí, SP, Brazil. Thus, it was concluded that the adjustment applied to monthly and annual ET data produced results statistically correlated to those obtained through a simplified annual water balance, confirming that the developed methodology can be used to estimate monthly and annual ET from Landsat 8 imagery and the hybrid ET model.

Keywords: Landsat 8, two source energy balance, remote sensing, water balance

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VALIDAÇÃO DE UM MODELO HÍBRIDO DE EVAPOTRANSPIRAÇÃO UTILIZANDO IMAGENS DE SATÉLITE E DADOS DE CHUVA-VAZÃO

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2 RESUMO

Para quantificar o balanço hídrico em bacias hidrográficas, é necessário conhecer os componentes do ciclo hidrológico, especialmente, a evapotranspiração (ET). Muitos estudos têm sido realizados utilizando um modelo de fonte única como o SEBAL para estimar a ET real (ETa) a partir de imagens de satélite; contudo, outros modelos têm sido desenvolvidos e continuamente melhorados, tais como o Balanço Energético de Duas Fontes (TSEB). Este estudo avaliou a estimativa da ETa realizada por um modelo de ET híbrido de TSEB programado na Interface de Modelagem de Evapotranspiração Espacial (SETMI) utilizando imagens de satélite. A avaliação foi realizada ao longo de dois anos hidrológicos completos, desenvolvendo-se uma nova metodologia para converter os dados de ETa horários em dados mensais e anuais. Os resultados da aplicação do modelo TSEB/SETMI às imagens do Landsat 8 foram validados contra um de cálculo do balanço hídrico a partir de medições de campo em três bacias hidrográficas representativas de Corumbataí, SP, Brasil. Assim, concluiu-se que o ajustamento aplicado aos dados mensais e anuais da ET produziu resultados estatisticamente correlacionados aos obtidos através de um balanço hídrico anual simplificado, confirmando que a metodologia desenvolvida pode ser empregada em estimativas mensais e anuais da ET a partir de imagens do satélite Landsat 8 e do modelo de ET híbrido.

Palavras-chave: Landsat 8, balanço energético de duas fontes, sensoriamento remoto, balanço hídrico

3 INTRODUCTION

Water is essential for life on Earth, and, in recent years, water resources have been the focus of increasing concern in society. It is known that the agricultural sector consumes almost 69% of the water derived from rivers, lakes, and underground aquifers (MOREIRA *et al*., 2010). Therefore, the efficient use of water in agriculture and the development of new technologies for planning and optimization of water resources in river basins should be considered priority goals, both by public bodies and academia.

For this, it is necessary to obtain detailed knowledge of the components of the hydrological cycle, especially evapotranspiration (ET). Pereira, Villa Nova and Sediyama (1997) define evapotranspiration as a fundamental climate element composed of two processes: water evaporation on the surface of the soil and transpiration from plants. Evapotranspiration is strongly influenced by the type of vegetation, agricultural management, environmental management, and, above all, by climatic parameters (ALLEN *et al*., 1989), including solar radiation, wind, temperature, and relative humidity.

To estimate evapotranspiration, Moreira *et al*. (2010) states that traditional methods, such as water balance in the soil, were developed for specific applications and may not match the result obtained by spatially analyzing crops. Consequently, other methods are being developed, especially in Geographic Information Systems (GIS), using satellite imagery to get actual and spatialized data representing a point in time.

Alternatives to the classical methods of estimation are increasingly employed, as in the case of the Surface Energy Balance Algorithm for Landsource (SEBAL) source model, which not consider the water balance in the process to obtain the actual evapotranspiration results. Other more elaborate, accurate, and comprehensive models are also being presented in literature, such as the Two-Source Energy Balance (TSEB).

The TSEB model is known to be used to estimate the actual ET, splitting between soil and vegetation. One of the main advantages of TSEB is that the model estimates evaporation (E) and transpiration (T) separately using radiometric temperature information and biophysical parameters of the vegetation, which are available from satellite imagery (BELLVERT *et al.*, 2021). This influence of vegetation on ET results does not happen in other models of ET calculation by remote sensing, such as SEBAL.

Bastiaanseen *et al.* (2005) used SEBAL to studies his accuracy at field in some regions of the world. They used a satellite-based measurement to validate and establish links between energy balance on the surface with water use.

Timmermans *et al.* (2007) used the TSEB in various scenarios and locations and concluded that the model showed more accurate and precise results for each crop and exposed soil than the one-source model, as TSEB does this analysis separately. Therefore, TSEB is preferred for studies with previously determined land use in known areas, such as river basins.

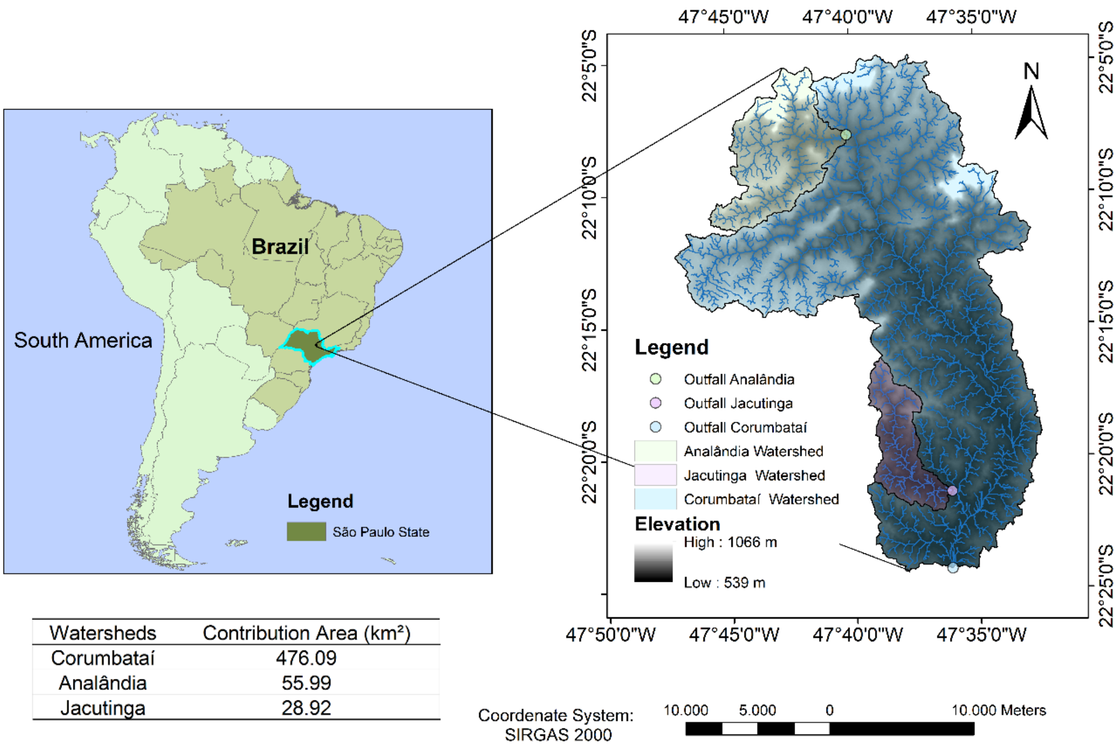
Thus, the aim of this paper was to propose a new methodology to estimate spatialized actual evapotranspiration, adjusting daily data to monthly and annual spatialized actual ET using TSEB in three watersheds in the state of São Paulo, Brazil, with monitored rainfall and flow rates.

4 MATERIAL AND METHODS

4.1. Study area

For this study, was selected three monitored watersheds with rainfall and flow measurement stations at the control section point (outfall) of each watershed. All three basins are in the region of Corumbataí, SP, Brazil (Figure 1).

Figure 1. Location of the studied watersheds in the state of São Paulo.



Watersheds	Contribution Area (km²)
Corumbataí	476.09
Analândia	55.99
Jacutinga	28.92

The climate in the region of the studies is the Cwa, according to Köppen, defined as subtropical mesothermic, with dry winter and rainy summer, temperatures of the hottest month exceeding 22ºC and the coldest month not exceeding 18ºC. The rains are concentrated in the months of October to March, presenting an average annual precipitation of 1,390 mm (TROPPMAIR; MACHADO, 1974), with the dry period from April to September. The winds predominate in the sense SE-NW (SETZER, 1966; MONTEIRO, 1973).

These basins have mostly Argissolo and Latosolo soils and are mainly covered by pasture and sugar cane plantations. The predominant relief in the basins are flatter areas (40% of the total area) (BOSQUILIA, 2016).

Also, the three watersheds are adjacent to each other, and two of these watersheds (Analândia and Jacutinga basins) are sub-basins of the larger watershed (Corumbataí basin). This enabled the use of the same surface and satellite meteorological data throughout the study area. Furthermore, the watersheds have large drainage areas that allowed the comparison and verification of the method in different scenarios.

These watersheds were outlined using the geographical coordinates of the location of the control sections obtained from the Water and Electricity Department of São Paulo State, Brazil (DAEE), and using the methodology presented by Bosquilia et al. (2015). To delineate the watershed, the research team used the ASTER-GDEM Digital Elevation Model (DEM) with 30 meters of spatial resolution.

4.2. Obtaining the data collected in the field

The telemetry network installed and maintained by the Water and Electricity Department of São Paulo State (Departamento de Águas e Energia Elétrica do Estado de São Paulo (DAEE)) provided the monthly average rainfall data (mm. month^{-1}) and monthly average flow (m³.s^{-1}, later transformed into mm. month^{-1}) for two hydrological years (April 2013 to March 2014, and from April 2014 to March 2015) for each watershed. Custódio and Llamas (1976) also showed that an annual water balance analysis based on the actual ET analysis could be used to study water deficiencies of crops.

The collected data was used to calculate the annual actual evapotranspiration of the three watersheds, according to a simplified formula of water balance, where the storage variation of the water in the basin is discarded, since there is no way to measure the infiltration of water in the soil using satellite imagery, making the comparison impaired later. (Equation 1) (CUSTÓDIO; LLAMAS, 1976).

$$ET = P - Q \qquad (1)$$

Where ET is the calculated evapotranspiration, P is precipitation, and Q is the integrated flow rate at the time of the basin control section. The estimation of ET from Equation 1 was used as the benchmark to assess and validate the results of the new hybrid evapotranspiration model.

4.3. Obtaining ET estimates using satellite imagery

To estimate actual evapotranspiration from satellite imagery, we used a new methodology and chose to work with a hybrid model of Two-Source Energy Balance – TSEB (NORMAN; KUSTAS; HUMES, 1995; LI *et al*., 2005) programmed in SETMI (Spatial EvapoTranspiration Modeling Interface), described by Geli and Neale (2012) and Neale *et al.* (2012), jointly developed by researchers at Utah State University and the University of Nebraska - Lincoln, both in the United States, detailed by Bosquilia (2016) in a doctorate dissertation and presented by Bosquilia *et al*. (2018).

A Landsat 8 (Path/Row 220/75) satellite image was obtained for each month of the two hydrological years of this study (24 images, with, at least, 90% of the area free of clouds), comprising the watershed region of the present work.

As shown in the work flowchart (Figure 2), the input data that the SETMI program (Table 1) requires to calculate the ETa estimate for each date is land use in the study region with some data of each analyzed land cover (using segmentation and visual classification of the targets); the composition of the bands 3, 4, and 5 of Landsat 8 Level-2 imagery (reflectance and atmospherically corrected using the Land Surface Reflectance Code (LaSRC) (VERMOTE *et al*., 2016); the image of the surface temperature in degrees Celsius, obtained from band 10 of the TIR sensor of the Landsat 8 satellite (also atmospherically corrected using NASA's Atmospheric Correction Parameter Calculator, presented by Brunsell and Gillies (2002) and Barsi, Barker and Schott (2003) and validated by Barsi *et al*. (2005); and weather data from the study area, previously interpolated for the time (hour and minute) of the satellite pass for each of the 24 dates.

Figure 2. Flowchart of the methodology used to estimate the actual evapotranspiration (ETa) proposed in this study.

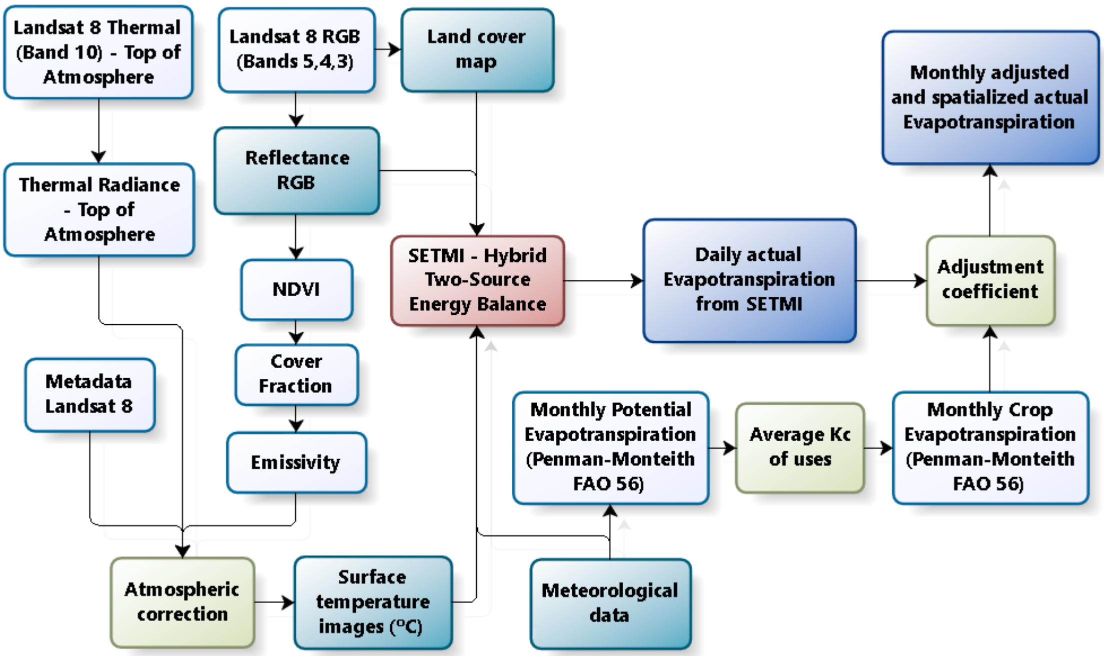


Table 1. Data from each Land Use Land Cover (LULC) present in the study area to be used in the Spatial EvapoTranspiration Modeling Interface (SETMI)

LULC	Kcbini	Kcbmid	Kcbend	Llast	Root Depth (m)	Min Cover Height (m)	Max Cover Height (m)	p
Planted Forest	1.2	1.2	1.2	362	2	0.1	18	0.5
Native Forest	1.2	1.2	1.2	362	2	0.1	12	0.5
Sugarcane	0.15	1.2	0.7	140	1.5	0.1	3	0.65
Bare soil	0.15	0.15	0.15	362	0.1	0.1	0.1	0.5
Grass	1	1	1	362	1	0.1	0.5	0.5
Built área	0.15	0.15	0.15	362	0.1	0.1	0.1	0.5
Other uses	0.15	1.2	0.15	34	1	0.1	3	0.5
Water	0.15	0.15	0.15	362	0.1	0.1	0.1	0.5

Where: Kcbini is the initial basal crop coefficient (Kcb) of the crop; Kcbmid is the intermediate-stage Kcb of the crop; Kcbend is the final Kcb of the crop; Llast is the final period of crop development, in days; Min Cover Height is the minimum height of the cover, in meters; Max Cover Height is the maximum height of the cover, in meters; p is the depletion fraction.

In the SETMI interface, by the programming used, land uses that have no Kc need to be entered with the minimum Kc (0.15).

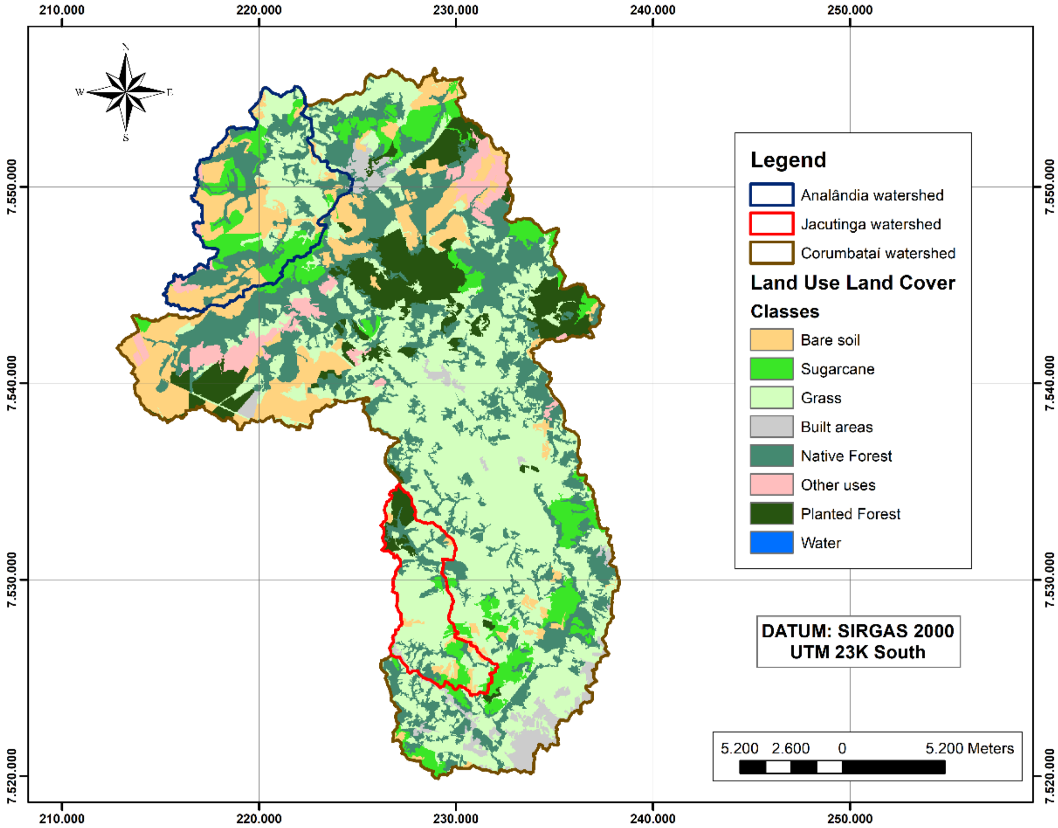
4.4. Adjustment of daily ET estimates to monthly estimates

To develop the methodology proposed in this study, which was originally presented in a doctoral dissertation by Bosquilia (2016), it was decided to extrapolate an estimate of actual ET, which is calculated, from the satellite image on a specific day of the month for the purpose of representing the ET of an entire month. This methodology developed was able to compensate the ET of the day of the satellite pass, since the data obtained on that specific day might not represent the reality of the site for most of the represented month.

For this, meteorological data obtained from the National Institute of Meteorology (INMET) were selected for each satellite passage date and used as a basis for calculation to obtain the Reference Evapotranspiration (ETr), which was estimated using the Reference Evapotranspiration Calculator (RefET), created, and presented in its latest version by Allen (2008). This program contains an automated way to calculate daily ETr using the Penman-Monteith (PM) method, described by Monteith (1965) and adapted by Allen *et al*. (1989). This is the method currently recommended by the Food and Agriculture Organization of the United Nations (FAO) (ALLEN *et al*., 1994).

The estimate of the daily reference ET for the day of the satellite pass, obtained with the Penman-Monteith method, was multiplied by the average Kcbmid value (intermediate stage for all land uses) in the studied area (which was 0.78, in this case, according to the Land Use Land Cover (LULC) obtained in the area, which was performed by segmentation of the satellite image and subsequent visual classification directly on the screen - Figure 3) to transform ETr into crop ET, considered the actual ET on the day of the satellite pass.

Figure 3. Land Use Land Cover (LULC) of the studied watersheds.



With this, these calculated daily values of actual ET based on the Penman-Monteith (PM) method were multiplied by the number of days of each month to obtain the monthly estimates of actual ET from PM estimation. This same multiplication by the number of days of each month was also performed for the estimate of actual ET obtained from the satellite images. Thus, for both methods, monthly estimates of actual ET were obtained.

For the actual ET estimate obtained by satellite images, it was necessary to calculate the average ET presented by the digital number (DN) of pixels within the area of each land use.

The monthly actual ET values (PM) were divided by the monthly actual ET values (satellite imagery - TSEB) to obtain an average coefficient for all months of the study. This coefficient was the representation of the relationship between the two monthly actual ET estimation methods studied.

With this, the calculated coefficient was used to adjust all the actual monthly ET values obtained by the satellite imagery (TSEB). Thus, this coefficient, now corrected and extrapolated from a single day of the month, could represent the monthly ET estimate. This estimate was compared to the water balance of the three watersheds monitored in the present study.

Finally, the monthly ET values, obtained from the water balance and the satellite estimation, were integrated for the two annual series, and compared to evaluate the use of the actual ET from TSEB and orbital data in the water balance estimation in watersheds.

5 RESULTS AND DISCUSSION

The entire process completed in this study resulted in the monthly data of the actual evapotranspiration adjusted by the Two-Source Energy Balance (TSEB) using Landsat 8 satellite imagery for the 24 studied months (Figure 4).

Figure 4. Actual monthly evapotranspiration (ET) values using the Two-Source Energy Balance (TSEB), adjusted by the methodology proposed in the present work for the three studied watersheds.

An analysis of Figure 4 revealed that the monthly variation of the adjusted actual ET estimated using the TSEB follows the rainfall pattern of the region, with two defined seasons: a dry season from April to September, with less than 20% of the annual precipitation, and a rainy season from October to March, with more than 80% of the annual rainfall, as observed by Valente (2001), Tavares, Christofoletti and Santana (2007) and Mello and Zavattini (2016). Also, the results were similar to the ET estimates using the traditional method (Penman-Monteith).

After obtaining the monthly estimated ET values with the adjusted TSEB model, the ET for the watersheds was calculated based on the simplified monthly water balance (Equation 1) using the flow obtained at the outfall points of each watershed and rainfall, assessed through measurements in the automatic weather stations located at the outlet points of the watersheds.

Thus, the results of the monthly ET estimate were obtained and Pearson's correlation (at a significance level of $p < 0.05$) between the different estimation methodologies was presented in Table 2 and in Figures 5 and 6.

Table 2. Pearson's correlation estimate (at a significance level of $p < 0.05$) using monthly evapotranspiration (ET) from water balance using rainfall and flow (data made available by the Water and Electricity Department of São Paulo State (DAEE)) and from the Two-Source Energy Balance (TSEB) for the hydrological years of 2013/2014 and 2014/2015.

Years	Watershed		
	Analândia	Corumbataí	Jacutinga
2013/14	0.53692	0.51797	0.60680
2014/15	0.47244	0.49497	0.49386
Mean	0.50468	0.50647	0.55033

Figure 5. Scatter plot of the monthly evapotranspiration (ET) values estimated with the Two-Source Energy Balance (TSEB) and with the water balance calculated by using rainfall and flow data (from the Water and Electricity Department of São Paulo State (DAEE)) for the hydrological year 2013/2014 in the three studied watersheds.

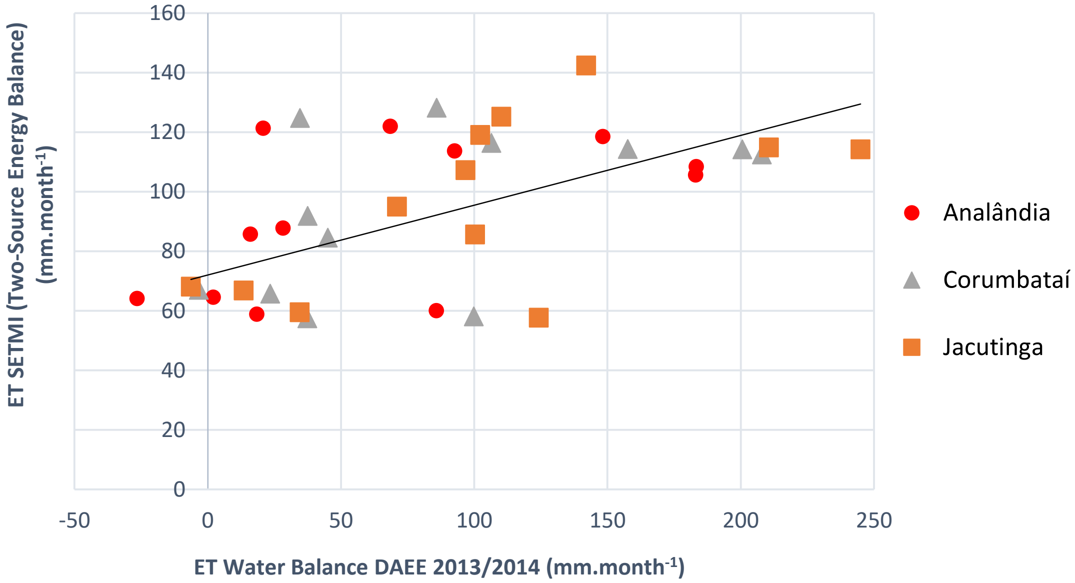
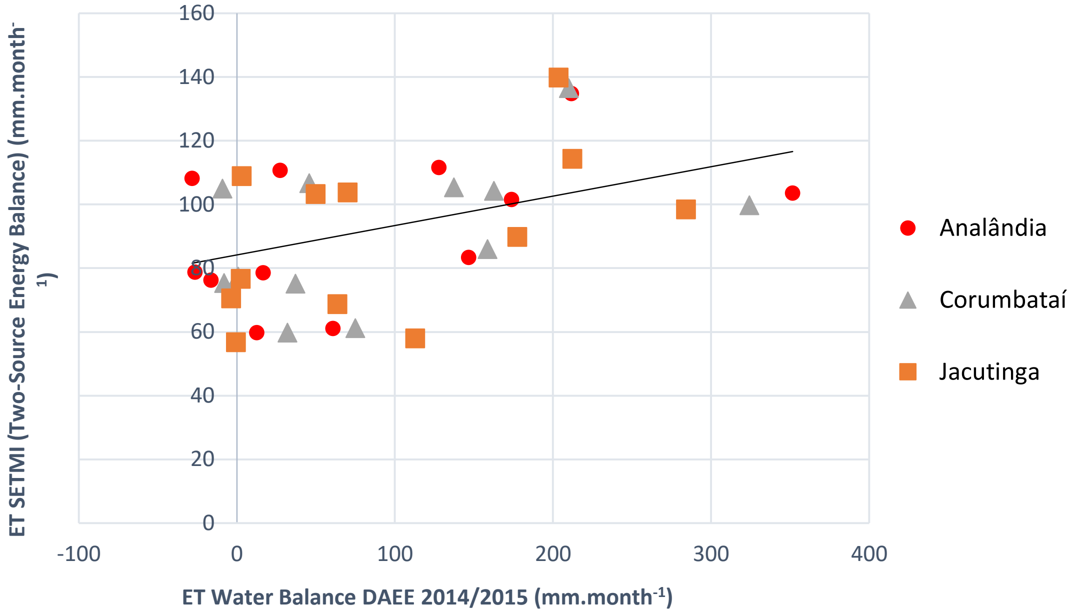


Figure 6. Scatter plot of the monthly evapotranspiration (ET) values estimated with the Two-Source Energy Balance (TSEB) and with the water balance calculated by using rainfall and flow data (from the Water and Electricity Department of São Paulo State (DAEE)) for the hydrological year 2014/2015 in the three studied watersheds.



Analyzing the results in Table 2 and Figures 5 and 6, the monthly ET estimate showed a moderate correlation (CALLEGARI-JACQUES, 2009) between the different estimation methodologies. The water balance provided months with high ET and other months with negative ET (the flow in these months was greater than the precipitation).

This can be explained by the difficulty in obtaining accurate flow and precipitation data in watersheds, it is hard to obtain near-actual monthly ET estimated using the simplified water balance since the time of concentration of a large basin can exceed one month, and the field measurements can be prone to interference and errors.

Another factor that should also be considered in the monthly water balance is the fact that the period of one month is too short for the entire cycle of Evapotranspiration-Precipitation-Runoff to be completed, with part of the water infiltrating the soil and taking longer to leave the basin when reaching the water table.

Therefore, the simplified water balance requires a complete calculation in a hydrological year to eliminate the variation problem of the subsurface and underground storage of the watershed.

With this, all the monthly values were integrated into annual values, resulting in estimated annual ET values: (i) with the Two-Source Energy Balance adjusted using the Landsat 8 imagery, and (ii) with the simplified water balance using precipitation data measured directly in the watersheds (Tables 3 and 4).

Table 3. Annual evapotranspiration (ET) estimated from the water balance calculated by using rainfall and flow (data provided by the Water and Electricity Department of São Paulo State (DAEE)) and from the Two-Source Energy Balance (TSEB) for the hydrological year 2013/2014.

Watershed	ET Balance (mm.year $^{-1}$)	ET TSEB (mm.year $^{-1}$)	Difference (mm.year $^{-1}$)	Variation (%)
Analândia	820.78	1111.76	290.98	26.17
Corumbataí	1033.64	1136.54	102.89	9.05
Jacutinga	1244.33	1157.02	87.32	7.55
r (Pearson)	0.999		Mean	14.25

Table 4. Annual evapotranspiration (ET) estimated from the water balance calculated by using rainfall and flow (data provided by the Water and Electricity Department of São Paulo State (DAEE)) and from the Two-Source Energy Balance (TSEB) for the hydrological year 2014/2015.

Watersheds	ET balance (mm.year $^{-1}$)	ET TSEB (mm.year $^{-1}$)	Difference (mm.year $^{-1}$)	Variation (%)
Analândia	1058.48	1108.02	49.54	4.47
Corumbataí	1166.59	1092.13	74.45	6.82
Jacutinga	1175.44	1088.63	86.81	7.97
r (Pearson)	-0.995		Mean	6.42

Additionally, the annual results were subjected to Pearson's correlation coefficient, with the use of trend lines, to evaluate the degree of linear correlation between the studied variables, as shown in Figures 7 and 8.

Figure 7. Scatter plot of the annual evapotranspiration (ET) values estimated with the Two-Source Energy Balance (TSEB) and with the water balance calculated by using rainfall and flow data, provided by the Water and Electricity Department of São Paulo State (DAEE), for the hydrological year 2013/2014 in the three studied watersheds.

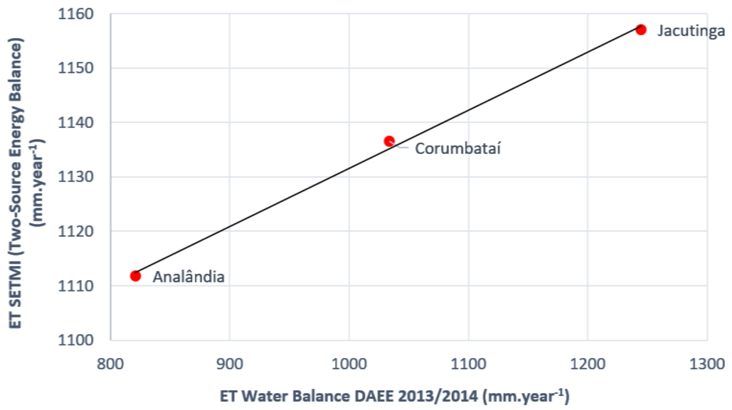
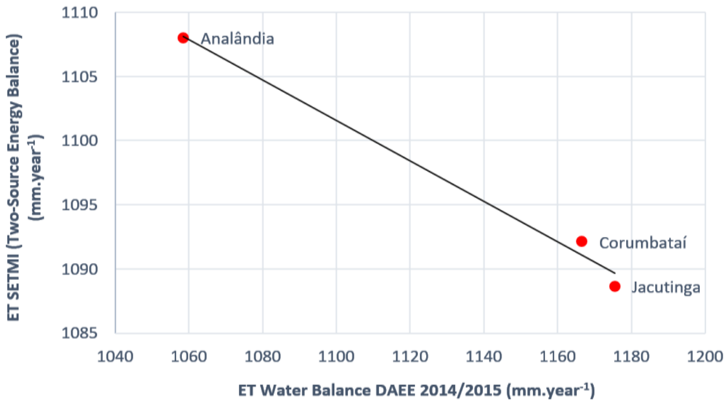


Figure 8. Scatter plot of the annual evapotranspiration (ET) values estimated with the Two-Source Energy Balance (TSEB) and with the water balance calculated by using rainfall and flow data, provided by the Water and Electricity Department of São Paulo State (DAEE), for the hydrological year 2014/2015 in the three studied watersheds.



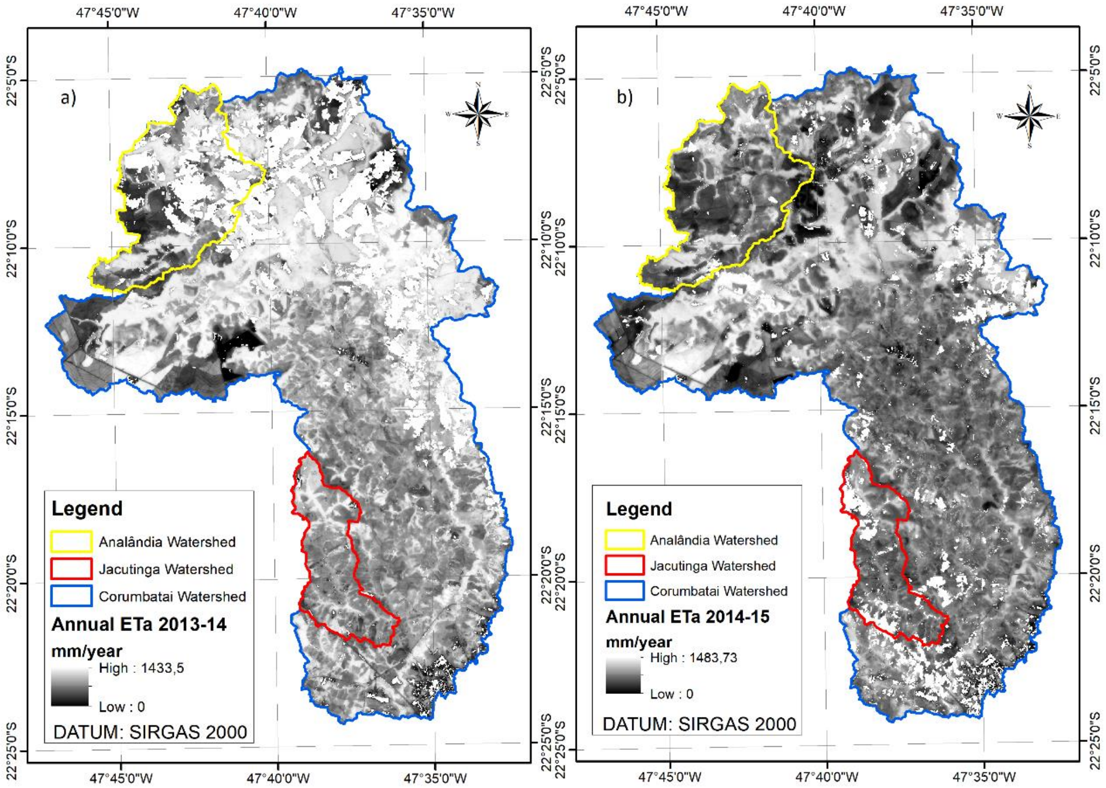
Tables 3 and 4 and Figures 7 and 8 show that the Pearson correlation coefficients were above 0.99, revealing an extremely high correlation between the variables (CALLEGARI-JACQUES, 2009). In this case, even presenting only three points in each studied year, a tendency line was observed close to the observations, with the average variations of 14.25% for the years 2013/14 and 6.42% for the years 2014/15.

The gross annual ET values presented here, especially in the Corumbataí and Jacutinga basins, showed a difference of under 10%, which is considered good, given the difficulty in obtaining flow and rainfall data in the field. This value can also be regarded as acceptable, as part of the water of the basins is stored or drained to another point that is not the main watercourse, from where the annual runoff volume was measured.

One explication for the greater variation of the Analândia basin in the hydrological year 2013/2014 can be a significant interference caused by the historical drought in that region during those years, possibly affecting the results, since the runoff data was obtained on the outfall of the basin. Moreover, the region has a more rugged relief and a greater altitude than the other areas. This fact may lead to greater differences in precipitation in certain parts of the watershed. These differences may not have been accounted for the rainfall measured at the mouth since it may not correctly represent rainfall upstream in the watershed.

Results presented by Bastiaanseen *et al*. (2005) show that SEBAL can obtain valid results for daily and seasonal spatialized evapotranspiration using field data, but not considering land use to obtain these results in the model. The adjustment for a hybrid model used in this work (TSEB with water balance) presented valid results, including an annual spatialized actual ET image to know how the water use of each land use is (Figure 9).

Figure 9. Annual adjusted and spatialized ETa for the three studied watersheds: a) 2013-14; b) 2014-15.



Although some of the values could reflect differences between the methods, it was concluded by the research team that the adjusted model in this study can be used as a new methodology to estimate the actual evapotranspiration at the satellite pass, and the actual monthly and annual ET values. Therefore, this methodology can potentially generate actual spatialized ET imagery that can be unique for each type of plant cover in these imageries.

6 CONCLUSION

The analysis of the proposed methodology of evapotranspiration (ETa) estimation using the Two-Source Energy Balance for three watersheds showed that the adjustment from daily to monthly ETa provided statistically correlated annual values that are similar to those obtained with the simplified annual water balance calculated by using rainfall and flow values measured at the field in the study areas.

Thus, it is concluded that the proposed adjustment for the model was validated and can potentially provide monthly and annual spatialized evapotranspiration data for large areas, separated by each type of Land Use Land Cover.

It is expected that, with this methodology, other works can be developed so that satellite imagery can be used to estimate the water balance in large hydrographic basins, since this field work is difficult for large areas.

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