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Temporal-spatial Control of the difference between Precipitation and Evapotranspiration in Paracatu Sub-basins

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***Abstract*— *Water availability control may be relevant regarding the rational use of water resources. Thus, the objective of this work was to use remote sensing techniques as a tool to assist the control of the decendial difference between precipitation and evapotranspiration (S_p) in sub-basins of the Paracatu River. Negative values of S_p were observed in almost the complete study area, therefore, indicating that the region was in the dry season. In terms of water balance, the knowledge of the spatial-temporal of the S_p component can help the planning and control of water resources in watersheds with strong water demand by irrigated agriculture. It is recommended the execution of field validations by installing towers for measurements of the components of the energy balance, as well as the monitoring of the development and growth phases of the crops in association with water balance for each type of use of the land.*
***Keywords*— basin management, land use, Sebal, water resources.**

I. INTRODUCTION

Water demand control and availability on a large scale are of paramount importance for the management of water resources in a river basin [1, 2]. Thus, the knowledge of the water availability in both space and time may be essential to assist the rational use of water resources, while alleviating the risks of loss of crop productivity through decision-making directed to an efficient and sustainable water planning. According to Rollenbeck and Anhuf [3], evapotranspiration (ET) is the main link between hydrology and meteorology as it contributes, in a significant way, in the partition of energy balance at the surface and on the regional water balance.

Regarding ET estimation, several methods have been proposed, such as the energy balance based on Bowen's ratio and the method of turbulent correlations. However, these methods are precise and require a large number of field measurements to achieve a sufficiently distributed data density for the spatialization of ET estimates on a regional scale [4]. As a result, the use of remote sensing techniques has become a potential tool for the determination of energy flows and, therefore, of large-scale ET [5, 6, 7, 8, 9], therefore, algorithms and models are used.

Surface Energy Balance for Land (SEBAL) is an algorithm that with the use of few field data, allows the estimation of the energy fluxes that occur at the soil-vegetation-atmosphere interface with not many field data [10, 11]. This algorithm has been developed in a modular way, allowing other models to be used to estimate large scale water balance components, such as the difference between precipitation and ET [1].

Water balance quantifies the water flows; that is, it calculates the inputs and outputs of water in a physical unit, which can be a river basin in a particular time interval. In general, water inflows can occur through precipitation and irrigation, and the outflows by surface runoff and ET. The difference between precipitation and ET is the first component to be determined in a water balance.

Therefore, the objective of this work was to apply the SEBAL algorithm together with MODIS (Moderate Resolution Imaging Spectrometer) data as a tool to assist the control of the decendial difference between precipitation and ET in Paracatu river sub-basins.

II. MATERIAL AND METHODS

The Paracatu river basin is located in the middle of the São Francisco river. It drains an area of approximately 45,600 km², being the second largest sub-basin of the São Francisco river. It is located almost entirely in the state of Minas Gerais (92%), including only 5% of its area in the state of Goiás and 3% in the Federal District [12]. The sub-basins of Entre Ribeiros and Preto rivers, the object of this study, represent about 30% of the area of the Paracatu basin. These two sub-basins, located in Alto Paracatu, cover part of the territories of the Federal District and the States of Minas Gerais and Goiás (Figure 1).

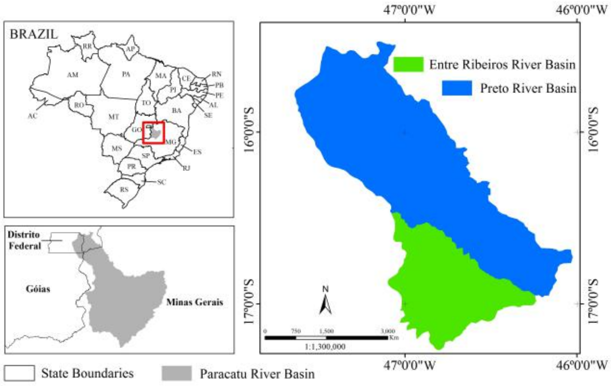

Fig. 1: Location of the study area.

The climate in the region of study is rainy tropical, with rainfall concentrated from October to April; November, December and January stand out as the rainiest months as it can be seen in Figure 2. The annual average precipitation is of 1,338 mm, while the average annual evapotranspiration is 1,140 mm [13]. The primary uses of water resources in the sub-basins of Entre Ribeiros and Preto rivers are to meet the demands of urban, animal, and irrigation supplies. In the Paracatu basin, most of the irrigated areas are concentrated in the headwaters up to half of their drainage system, especially in the Entre Ribeiros stream and the Preto river, which correspond to 53% of the irrigated area identified in the basin by the Director Plan of Water Resources of Paracatu Basin [13].

The products of the MODIS sensor: MOD09GA (surface spectral reflectance, bands 1 to 7), MOD11A1 (surface temperature, bands 31 and 32) and MOD07 (zenith angle) of days 2, 16 and 23 of September 2007 were obtained in the HDF (Hierarchical Data Format) and converted to the GeoTIFF format using the MRT (MODIS Reprojection Tool) software. Apparently, the selected images were cloudless.

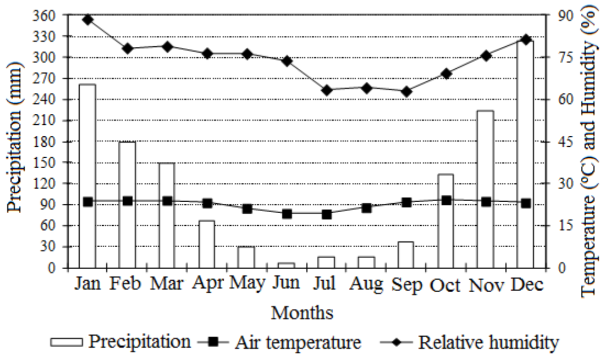

Fig. 2: Monthly average data of rainfall (mm), air temperature (°C), and air relative humidity (%) for the municipality of Paracatu-MG.

Wind speed and incident shortwave radiation data from the automatic meteorological station (A542) located in the Municipality of Unaí, MG, were used. Also, daily rainfall data from 16 stations were used to estimate the difference between precipitation and evapotranspiration (S_P). Figure 3 shows the spatial distribution of the ten rainfall stations from the Brazilian Water Agency (ANA) and the six meteorological stations owned by the Brazilian Institute of Meteorology (INMET), of which two are automatic, and four are conventional.

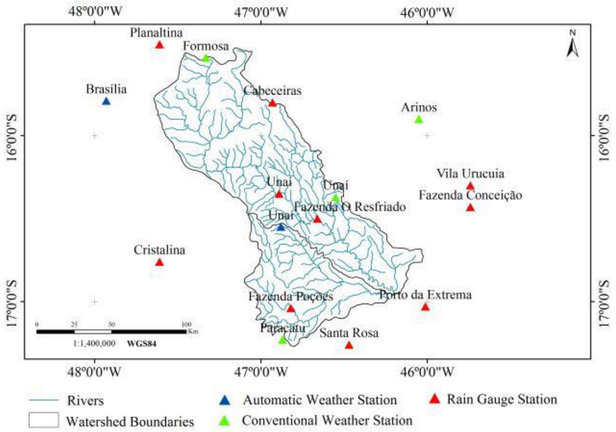

Fig. 3: Location of rainfall stations of the Brazilian Water Agency (ANA) and automatic and conventional meteorological stations of the Brazilian Meteorological Institute (INMET).

In order to obtain the decendial evapotranspiration, the processing steps of the SEBAL algorithm were performed. Thus, the radiation balance (Rn) was the first component of the energy balance to be obtained. For this, the equation suggested by Allen et al. [14] was used:

$$Rn = R_{s\downarrow} - \alpha R_{s\downarrow} + R_{L\downarrow} - R_{L\uparrow} - (1-\varepsilon_o) R_{L\downarrow}$$

Where: $R_{s\downarrow}$ is the incident short-wave radiation (W m^{-2}), α is the surface albedo (dimensionless), $R_{L\downarrow}$ is

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the long-wave radiation emitted by the atmosphere (W m-2), $R_{L\uparrow}$ is the longwave radiation emitted by the surface (W m-2), ε_o is the emissivity of the surface (dimensionless).

Then, heat flux in the soil was determined:

$$G = \left[\frac{T_s}{\alpha}(0,0038\alpha + 0,0074\alpha^2)(1 - 0,98\,NDVI^4)\right]Rn$$

Where: G is the heat flux in the soil (W m-2), T_s is the surface temperature (°C) relative to the product MOD11A1, NDVI is the vegetation index of the normalized difference (dimensionless).

Then, the sensible heat flux was obtained. It expresses the rate of heat transferred from the surface to the air through the convection and conduction processes.

$$H = \frac{\rho c_p\, dT}{r_{ah}}$$

Where: H is the sensible heat flux (W m-2), ρ is the density of the moist air (1.15 kg m-3), c_p is the specific heat of the air at constant pressure (1004 J kg-1 K-1), r_{ah} is the aerodynamic resistance to the sensible heat flux (s m-1), dT is the difference of the air temperature between two levels above the surface, that is, at the height of 2.0 m and 0.1 m.

The latent heat flux (LE) was calculated as the residue of the energy balance equation, through the simple difference between the balance of radiation and soil and sensible heat fluxes.

$$LE = Rn - G - H$$

By using the energy balance components, it was possible to calculate the evaporative fraction (λ) using the expression suggested by Bastiaanssen et al. [11]:

$$\lambda = \frac{LE}{LE + H} = \frac{LE}{Rn - G}$$

The evaporative fraction was used to estimate the decendial evapotranspiration through the equation:

$$ET_{dec} = n\,\lambda\,\overline{Rn_{24h}}$$

Where: ET_{dec} is decendial evapotranspiration (mm dec-1), n is the number of days in the considered ten-day period, $\overline{Rn_{24h}}$ is the average radiation balance in each ten-day period (W m-2d-1).

The daily precipitation data for each station were accumulated in ten-day periods, which were defined as follows: D1 = days 1 to 10; D2 = days 11 to 20 and D3 = days 21 to 30. After that, data interpolation was carried out, and the spatialization of decendial precipitation was performed. Next, the decendial difference between precipitation (P_{dec}) and evapotranspiration (ET_{dec}), named S_p was estimated:

$$S_p = P_{dec} - ET_{dec}$$

III. RESULTS AND DISCUSSION

Figure 4 shows the LE maps for the sub-basins of Entre Riberios and Preto river. However, it can be seen in Table 1 the statistical data for LE, ET_{dec}, and Sp. According to the maps of Figure 4, it is possible to notice a high variability in LE. The values of LE between 0 and 200 W m-2 (yellow and orange shade) predominated in most of the sub-basins in the estimates for the first ten days of September (Figure 4A), while for the second (Figure 4B) and the third (Figure 4C) ten-day periods, values between 200.1 and 400 W m-2 (green and light blue shade) predominated. Besides, in some of the region on the Vereda Grande creek and the Entre Ribeiros and São Pedro streams, LE values between 400.1 and 500 W m-2 (dark blue) were observed. These higher values are justified both by the presence of water bodies and by the area of riparian forest, as shown by the area highlighted in Figure 4C. In a study carried out in the city of Patos, state of Paraíba, Gomes et al. [15] found values of LE ranging from 4.71 to 598 W m-2, with the highest values observed on water bodies. Besides, the authors point out that LE reached the value of 420 W m-2 in areas covered by vegetation and in the sub-basin of the Espinharias river.

The negative values (black shade) were observed for the three ten-day periods of LE estimation, mainly in areas of the Upper Preto river in estimates for the first and third ten-day (Figures 4A and 4C, northern portion highlighted in a dotted rectangle on the map). Arya [16] points out that the values of H, LE, and G are generally positive during the day. In exceptional circumstances, such as irrigated fields, H and, or, G assume negative values, whereas LE, due to evaporative surface cooling, may exceed the surface radiation balance. According to this author, the magnitudes of energy balance components depend on many factors, such as surface type and its characteristics (soil moisture, texture, vegetation, etc.), geographic location, season, time of day and climate. Another justification for obtaining negative values may be possible cloud contamination of the pixel, which disguises the expected results for a specific region.

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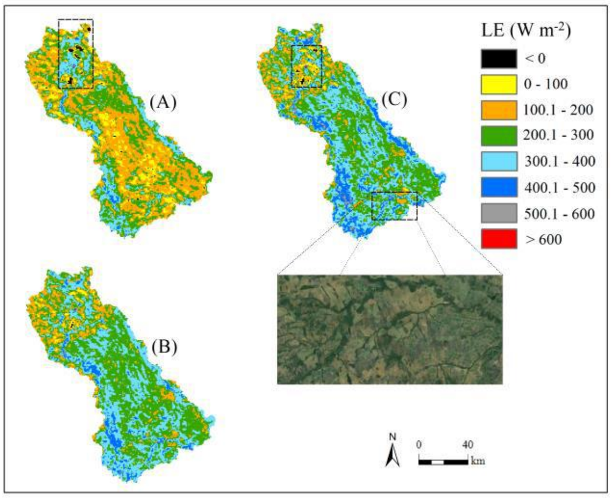

Fig. 4: Latent heat flux maps (LE, W m^{-2}) for September 2 (A), September 16 (B) and September 23 (C) 2007. A prominent view of part of the stream Vereda Grande and Entre Rios and São Pedro (C).

In the study by Nicácio [17], negative values of LE were found in most of the area occupied by open native vegetation, exposed soil areas, and urbanized regions. This author points out that a possible reason for this behavior may be attributable to the occurrence of lower values of the balance of radiation associated to the increase of the amount of energy destined to the heating process of the air and the soil. Another justification may be related to the type of land use and cover, in this case, Andrade et al. [6] observed that this factor influenced the values obtained for the components of the energy balance. For example, if the area represented by a MODIS pixel has considerable heterogeneity of use and coverage, then the resulting value of LE will be influenced by the degree of intensity of this heterogeneity. Aguiar et al. [18] state that because of the spatial resolution of MODIS, a scene element, corresponding to a pixel of the image, may include more than one type of land cover and the detected radiance will be represented by the integration, called blending, of all objects contained in the scene element.

Table 1 shows that average LE varied between 202.98 ± 87.28 and 292.39 ± 90.19 W m^{-2}. The minimum and maximum values, -158.59 and 696.72 W m^{-2}, respectively, occurred on September 2, 2007. These results were within the range of maximum values found by Mendonça [19] who estimated values between 417.44 and 829.71 W m^{-2} by using the proposition "Classical." The maximum values of LE also corroborate with the results found in studies conducted in the Brazilian Northeast by Bezerra et al. [20, 21].

Table 1: Minimum, average and maximum values and standard deviation (SD) of latent heat flux (LE, W m^{-2}), decendial evapotranspiration (ET_{dec}, mm) and decendial perception between rainfall and evapotranspiration (Sp, mm) observed for the sub-basin of Entre Ribeiros stream and Preto river

	LE (W m^{-2})			ET_{dec} (mm)			S_p (mm)		
Date	02/09	16/09	23/09	D1	D2	D3	D1	D2	D3
Min.	-158.59	-38.35	-73.41	0.00	0.00	0.00	-59.16	-61.99	-61.32
Max.	696.72	639.92	653.78	59.16	61.99	61.54	0.00	0.00	0.56
Average	202.98	279.75	292.39	20.89	30.17	30.30	-21.12	-30.41	-29.02
SD	87.28	78.03	90.19	8.36	7.42	8.32	8.36	7.42	8.31

Figure 5 shows the thematic maps of the ET_{dec} for the sub-basins of the Entre Ribeiros stream and Preto river. Average ET_{dec} varied between 20.89 ± 8.36 and 30.30 ± 8.32 mm, with minimum and maximum values of 0.00 and 61.99 mm, respectively (Table 1). For the three ten-day periods of September 2007, the high variability of ET_{dec} was evident, and this was probably due to the heterogeneity of areas (Cerrado, pasture, urban area, watercourses, irrigated areas with different types of crops, etc.).

Figure 5A shows that ET_{dec} between 10.1 to 20.0 mm (orange shade) predominated particularly in the Middle and Lower Preto Rivers. Also, the classes of ET_{dec} values within the ranges of 20.1 to 30 mm (green shade) and 30.1 and 40.0 mm (light blue shade) are highlighted. However, in the second and third ten-day period of September (Figures 5B and 5C) an increase in ET_{dec} was observed, where values ranging from 20.1 to 40.0 mm (green and light blue shade) predominated. In general, ET_{dec} was greater than 40 mm in areas over watercourses. In some cases, such as, for example, part of the Preto river that borders the States of Goiás and Minas Gerais (highlighted in the Figures 5B and 5C), values greater than 50.1 mm (gray shade) were observed.

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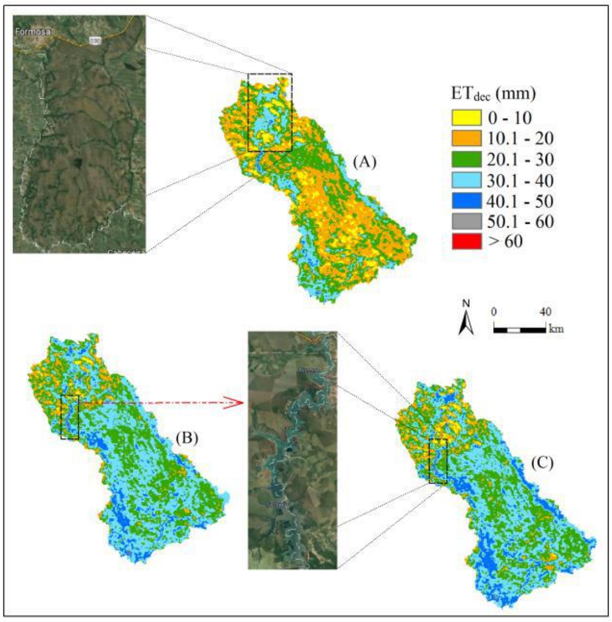

Fig. 5: Evapotranspiration maps (ET_{dec}, mm) for the first ten-day period (A), second ten-day period (B) and third ten-day period (C) of September 2007. Estimates made for the sub-basin area between Entre Ribeiros and Preto river. Cerrado (A) and part of the Preto river (B and C) are highlighted.

Figure 6 shows the thematic maps of S_p for the three ten-day periods of September 2007. It is noted that $S_p > -30$ mm were spatially more extensive in the first ten-day (Figure 6A). However, the inverse was observed for the second (Figure 6B) and the third (Figure 6C) ten-day period for September 2007.

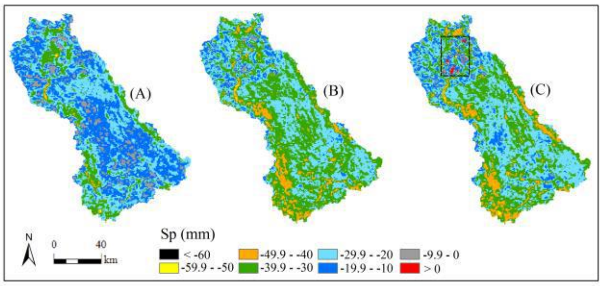

Fig. 6: Precipitation and evapotranspiration difference (S_p, mm) maps for the first ten-day period (A), second ten-day (B) and third ten-day (C) of September 2007. Estimates made for the sub-basins area of Entre Ribeiros stream and Preto River.

The occurrence of negative values in most sub-basin areas, except for small areas of red (> 0 mm) in the dotted rectangle of the northern portion of the basin (Figure 6C), indicates that the precipitation in the three ten-day periods was insufficient. This is because S_p will be positive when P_{dec} overcomes ET_{dec}. The average precipitation data of the conventional station of Paracatu, state of Minas Gerais (Figure 2) shows that September is a month characterized by the transition between dry and rainy season.

In the third ten-day in September, only the stations of Porto da Extrema (6.4 mm) and Unaí (11.0 mm) recorded rainfall volumes. These rains occurring until the second ten-day in October are essential in the restoration of the natural moisture of the soil and the supply of water demand by the vegetation. Meanwhile, later rains can contribute more significantly both to supply the water demand of vegetation and to recharge the aquifers on a regional scale. The total ten-days for October showed an increase in the occurrence of rainfall, and in the third ten-day, the rainy season may have started in the region. Minuzzi et al. [22] ratify this information, stressing that the rainy season in the sub-basin region, usually starts between October 13 and 22.

By using as an example the total precipitation recorded at the Paracatu station, in the state of Minas Gerais from September and October, it can be stated that the rains were below the historical average. In this case, the expected historical average for September and October is 35.9 and 132.8 mm, respectively. Thus, rainfall volumes below the historical average may justify the predominance of negative values of S_p in the three analyzed ten-day periods.

IV. CONCLUSIONS

For the three ten-day periods of September 2007, S_p was negative in almost the entire area of the sub-basins of the Entre Ribeiros stream and Preto river, therefore, indicating that the region was in the dry season, with rainfall records below the historical average for the period.

Overall, the use of MODIS sensor products to estimate S_p was relevant due to its extensive spatial coverage as well as the possibility of generating time series that help the understanding of surface biophysical processes in a river basin scale.

Estimates of S_p become an important variable in terms of water balance, being promising to assist in the planning and controlling of water basins with strong water demand by irrigated agriculture. However, regarding complementary studies, it is recommended that field validations are performed with the installation of towers for measurements of energy balance components as well as the monitoring of development and growth phases of crops in association with water balance for each type of land use.

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