Estimation of evapotranspiration in the Brígida River basin, Brazil, by satellite remote sensing

RICHARDE MARQUES SILVA[1], LEONARDO PEREIRA E SILVA[2], CELSO AUGUSTO GUIMARÃES SANTOS[2] & SUZANA MARIA GICO LIMA MONTENEGRO[3]

1 *Federal University of Paraíba, Department of Geosciences, 58051-900 João Pessoa, PB, Brazil*
richarde@geociencias.ufpb.br

2 *Federal University of Paraíba, Department of Civil and Environmental Engineering, 58051-900 João Pessoa, PB, Brazil*

3 *Federal University of Pernambuco, Department of Civil Engineering, Laboratory of Hydraulic, Av. Acadêmico Hélio Ramos, 50741-530 Recife, PE, Brazil*

Abstract During the past two to three decades, significant progress has been made in estimating actual evapotranspiration using satellite remote sensing. Recently, the remote sensing and the techniques of geoprocessing have been used in diverse areas of research, mainly in environmental monitoring. The present study was intended to analyse the applicability of the SEBAL algorithm (Surface Energy Balance for Land) for energy balance estimation in the Brígida River basin, located in a semi-arid region of Brazil between 39°11′56″W longitude and 8°38′55″S latitude and 40°49′36″W longitude and 7°15′43″S latitude. Two TM - Landsat 5 images, orbit 217 and path 65, on 24 September 2009 and 16 July 1990, were processed, organized and analysed in a Geographical Information System (GIS) environment from which surface albedo, vegetation indexes (NDVI, SAVI and LAI), surface temperature, soil heat flux, and evapotranspiration were determined. The results showed that the reduction of vegetation cover is evident in the temporal and spatial analysis between the two periods. This reduction produced an increase of the temperature. The estimated evapotranspiration values were compared with the measured data at Araripina meteorological gauge. It was further observed that evapotranspiration increased gradually from 1990 to 2009, with an annual rate of about 10%. When comparing the mean annual evapotranspiration estimated from SEBAL and the observed data for each period, there is a satisfactory agreement.

Key words SEBAL; semi-arid lands; water resources; Brazil

INTRODUCTION

Accurate estimation of evapotranspiration (ET) is considered to be the key factor in water resources management in semi-arid environments. Recently, computer-simulation models have been used to estimate ET from heterogeneous natural landscapes, which are in a dynamic state due to spatial and temporal interactions between the soil, vegetation and atmosphere (Bashir *et al.*, 2008).

Together with rainfall and runoff, the ET controls the availability of water at the Earth's surface (McCabe & Wood, 2006). The accurate determination of ET significantly reduces uncertainties in the water balance of a sub-basin (Cleugh *et al.*, 2007), thereby providing water managers with information on: (a) water resources being consumed and thus no longer available for downstream users, and (b) water productivity, i.e. the consumption of water in terms of biomass production per unit of water. Satellite image processing developments have provided the means to calculate ET as a residual of the surface energy balance to produce ET maps. These maps provide the means to quantify ET on a field by field basis in terms of both rate and spatial distribution (Allen *et al.*, 2007). The ET maps show the spatial distribution and evolution of ET during the years.

In this context, remote sensing is a tool that has enabled major advances in studies of water resources and application to areas with different types of coverage, and it can be used to estimate the radiation balance and its applications. Therefore, this study aims to estimate the surface energy balance from the Landsat 5 TM images with the use of the SEBAL algorithm (Surface Energy Balance for Land) for two different periods. SEBAL has been applied in Brazil for many irrigated areas in the semi-arid region, e.g. Bastiaanssen *et al.* (2001), Silva *et al.* (2005), Silva & Bezerra (2006), Allen *et al.* (2007), Bezerra *et al.* (2008), and Teixeira *et al.* (2009a).

Vegetation cover provides protection of the soil against erosion processes. In many regions of the world, vegetation cover shows high temporal dynamics. Long-term dynamics can be related to land-use conversions or gradual depletion of resources. Short-term dynamics are caused by rainfall characteristics and by human activities such as crop harvesting or burning practices. Many satellite remote sensing studies of water resources focus on the assessment of vegetation cover. These studies need to account somehow for the temporal variation, and consequently image timing is very important, although not always sufficiently highlighted (Silva *et al.*, 2007). Depending on the purpose of the study, sometimes a mono-temporal assessment can be sufficient. Canopy cover classification is often used to map vegetation types that differ in their effectiveness in protecting the soil, and are a key factor for ET estimation.

MATERIAL AND METHODS

Study area description

The research was conducted in the Brígida River basin (13 568 km^2) during the 1990–2009 seasons. The basin is located in the semi-arid region in the State of Pernambuco, northeastern Brazil, between latitudes 8°38′55″ and 7°15′43″S, and longitudes 39°11′56″ and 40°49′36″W (Fig. 1). The vegetation cover in Brígida River basin comprises caatinga (natural vegetation), which is classified as Steppe Savannah (bush and dense canopy) with species of the genera *Spondias*, *Mimosa* and *Aspidosperma*. The climate is hot and semi-arid, with annual precipitation ranging from 600 to 950 mm (30-year average), and a well-defined rainy season between December and April. The annual mean relative humidity is 70%, the rainfall regime in this region is characterized by an annual precipitation of around 860 mm/year, and the maximum daily rainfall in the area is 12 mm (Fig. 2). The annual average temperature is 28°C, with a daily temperature range of 26–29°C.

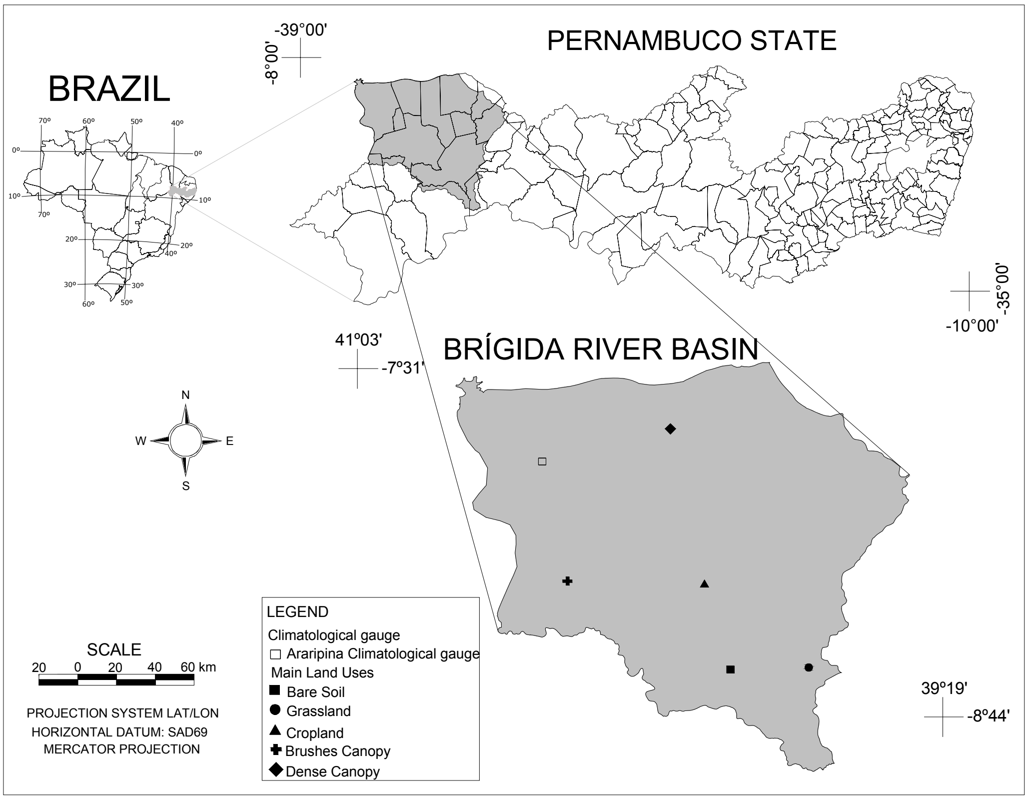

Fig. 1 Location of Brígida River basin and main land uses in the Pernambuco State and Brazil.

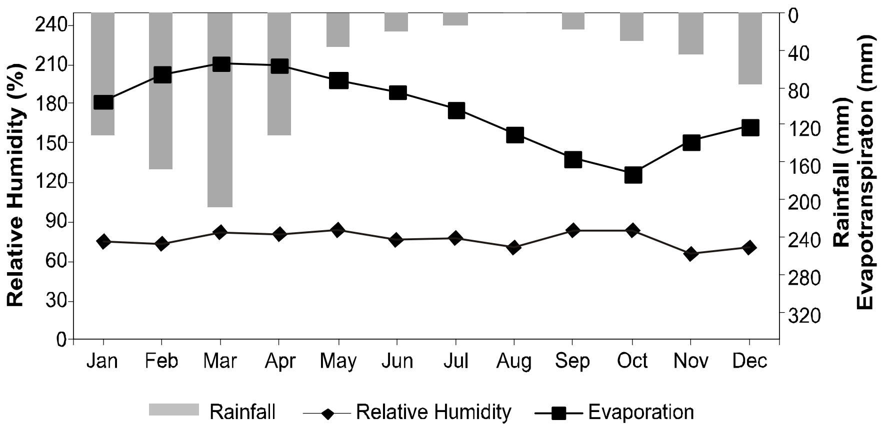

Fig. 2 Monthly mean of various climate variables for the period 1966–2000.

Brief outline of SEBAL major principles

SEBAL requires spatially distributed, visible, near-infrared and thermal infrared data, together with routine weather data. The algorithm computes net radiation (R_n), sensible heat flux (H) and soil heat flux (G) for every pixel, and the latent heat flux (λE) is acquired as a residual in the energy balance equation. This is accomplished by first computing the regional surface radiation balance, followed by the regional surface energy balance. A schematic overview of the conversion of spectral radiances into the net radiation using Landsat images is presented in Fig. 3. For more details, description and calculations of SEBAL, refer to Bastiaanssen *et al.* (1998).

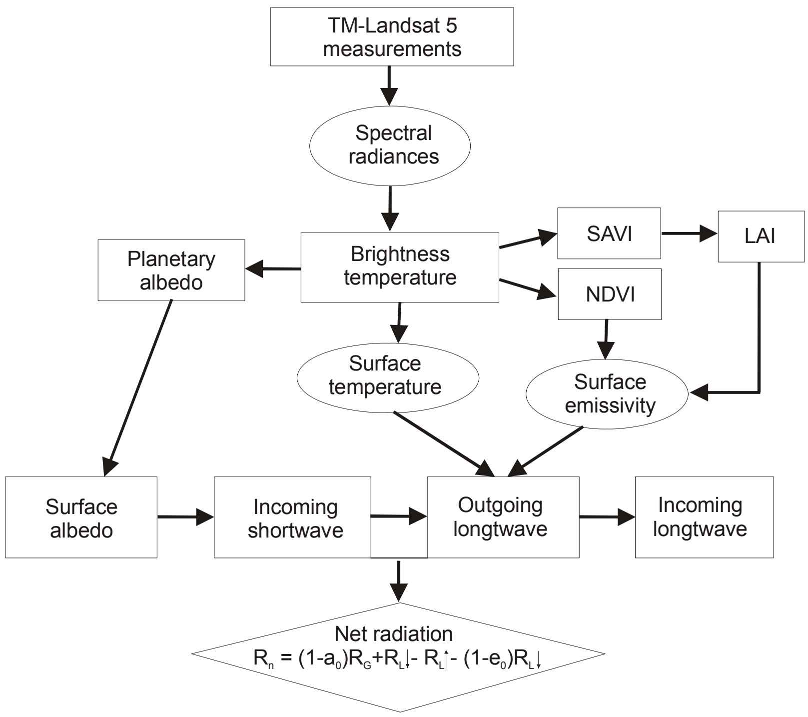

Fig. 3 Schematic flowchart for estimation of the radiation balance.

Two TM Landsat 5 images, orbit 217 and path 65 and 66, on 16 July 1990 (dry season) and 24 September 2009 (early wet season) were processed, organized and analysed in a GIS environment, to derive daily surface albedo, NDVI, SAVI, LAI, surface temperature, soil heat flux, and ET values. LAI is an indicator of biomass and canopy resistance to vapour flux, and is computed using an empirical equation stemming from equation (1) (Bastiaanssen *et al.*, 1998):

$$\mathrm{IAF} = -\frac{\ln[(0.69 - \mathrm{SAVI})]/0.59}{0.91} \quad (1)$$

where for TM Landsat 5 images, SAVI is based on top of atmosphere reflectance of Bands 4and 5:

$$\mathrm{SAVI} = \frac{(1+L)(\rho_{\mathrm{IV}} - \rho_{\mathrm{V}})}{(L + \rho_{\mathrm{IV}} + \rho_{\mathrm{V}})} \quad (2)$$

where SAVI is soil adjusted vegetation index (Huete, 1988), and L is constant (often L is set equal to 0.5), and ρ_{IV} and ρ_{V} correspond to Bands 4 and 5 of TM Landsat 5. The properties of this image are shown in Tables 1 and 2. The Landsat 5 TM imagery used in this study was obtained at 12:07 h local time on 16 June 1990 and 12:37 h local time on 24 September 2009. The atmospheric correction was made based on Allen *et al.* (2007), equation (3):

$$\alpha = (\alpha_{toa} - \alpha_p)/\tau_{sw}^2 \quad (3)$$

where α_{toa} represents the albedo planetary, α_p is the fractional path radiance (in this study it was set to 0.04, based on Bastiaanseen *et al.* (1998)), and τ_{sw} is the two-way transmittance to solar radiation for clear sky conditions (Allen *et al.*, 2007):

$$\tau_{sw} = 0.75 + 0.00002 \times z \quad (4)$$

where z is altitude (m) for each pixel, extracted from a Digital Elevation Model.

Five main canopy covers for analysis of the components of radiation balance and the accuracy of the algorithm SEBAL were chosen: (a) bare soil, (b) cropland, (c) grassland, (d) bush lands and (e) dense canopy (Fig. 1). The estimate data for two periods (1990 and 2009) were compared. In order to determine ET (mm/day), the methodology employed by Allen *et al.* (2007) and Bastiaanssen *et al.* (2001) was used.

Table 1 Spectral and spatial characteristics of Landsat 5 TM images.

Band	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6	Band 7
Wavelength (μm)	0.45–0.52	0.52–0.60	0.63–0.69	0.76–0.90	1.55–1.75	10.4–12.5	2.08–2.35
Resolution (m)	30	30	30	30	30	120	30

Table 2 Important properties of the Landsat-5 TM image used in this study (from metadata of the image).

Images	Sun elevation (°)	Sun azimuth (°)	Cloud cover (%)	Datum
June 16 (1990)	47	49	0–15	Sad-69
September 24 (2009)	28	78	0–35	Sad-69

RESULTS AND DISCUSSION

Figures 4 and 5 show the indexes estimated by SEBAL in 1999 and 2009 for the Brígida River basin. Based on the analysis carried out in this study, the Brígida River basin showed all indexes correspond to the range of values previously published in the literature for semi-arid regions of Brazil (Bezerra *et al.*, 2008; Teixeira *et al.*, 2009b). In July 1990 (dry season), the mean ET for bare soil, cropland, grassland, bush canopy and dense canopy are 0.27, 0.74, 0.77, 0.88, 0.98 mm/day, respectively (Table 3). In September 2009 (early wet season), the mean ET for bare soil, cropland, grassland, bush canopy and dense canopy are 0.24, 0.27, 0.32, 0.36, 0.55 mm/day, respectively (Table 3). These values correspond to areas of herbaceous vegetation (bush land and dense canopy), typically caatinga vegetation (Teixeira *et al.*, 2009b).

It was observed that there had been an increase in albedo and a decrease in NDVI, SAVI and LAI, when images from the dry season were compared to those from the rainy season. This is related to canopy cover loss.

This suggests that the natural vegetation (caatinga) cover has the ability of turning into a verdant green ecosystem during the rainy season.

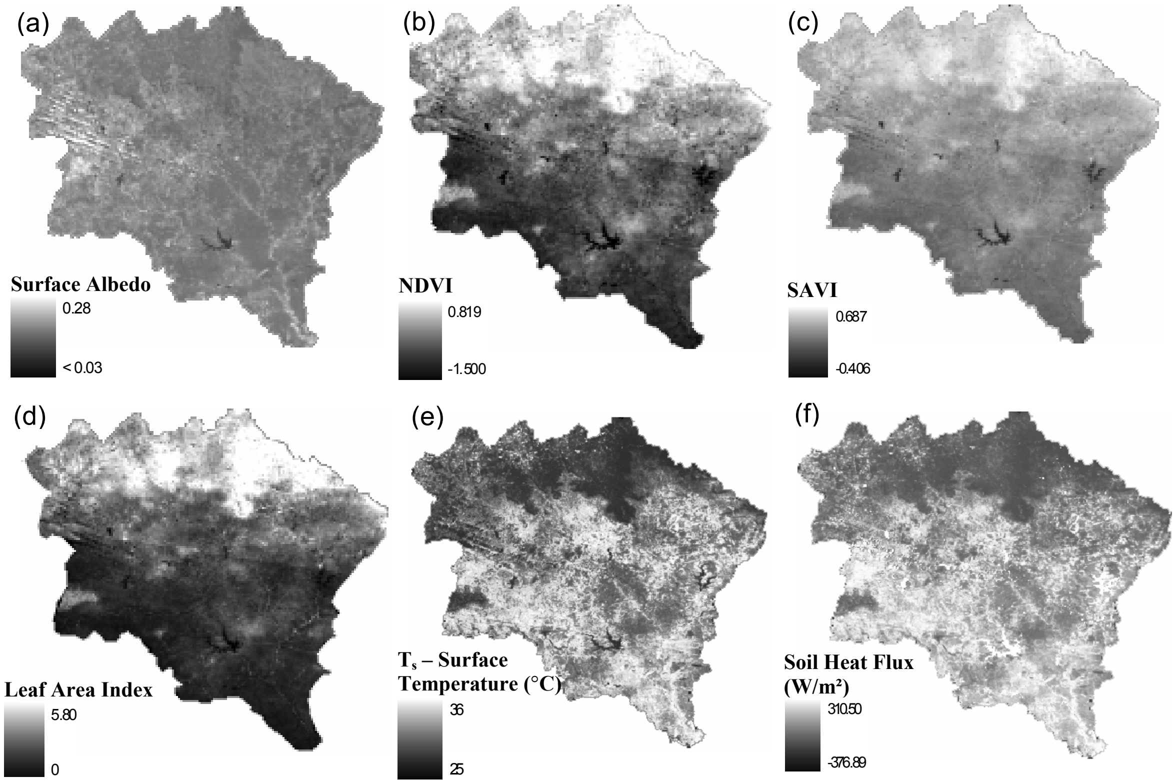

Fig. 4 Satellite-based maps of: (a) surface albedo, (b) NDVI, (c) SAVI, (d) LAI, (e) surface temperature and (f) soil heat flux estimated for 16 June 1990.

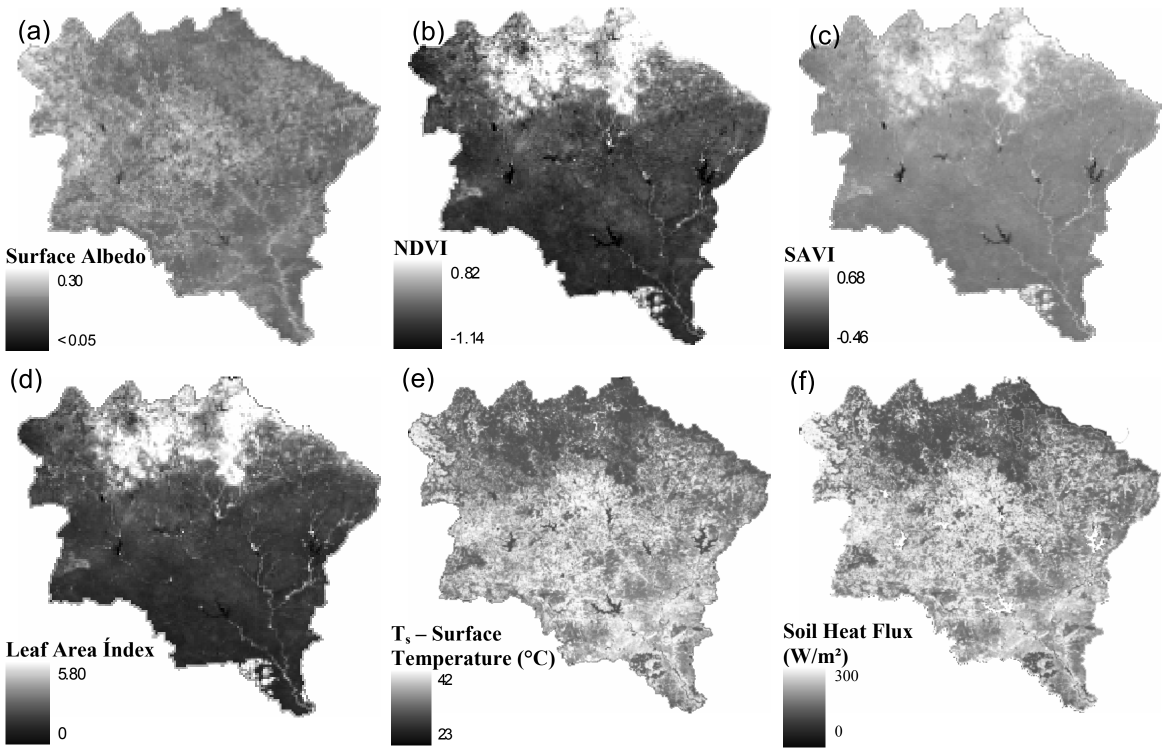

Fig. 5 Satellite-based maps of: (a) surface albedo, (b) NDVI, (c) SAVI, (d) LAI, (e) surface temperature and (f) soil heat flux estimated 24 September 2009.

Table 3. Statistical values of SEBAL parameters for different canopy covers in the Brígida River basin.

	Parameters	Canopy cover				
		Bare soil	Cropland	Grassland	Bush land	Dense canopy
16 June 1990	Surface albedo	0.181	0.077	0.079	0.072	0.059
	NDVI	0.288	0.436	0.356	0.487	0.711
	SAVI	0.268	0.316	0.264	0.348	0.508
	LAI	0.370	0.503	0.359	0.602	1.297
	T_s (°C)	26.35	26.78	25.91	23.66	19.92
	Soil heat flux (W/m²)	82.4	75.2	74.2	65.8	44.6
	ET (mm/day)	0.27	0.74	0.77	0.88	0.98
24 September 2009	Surface albedo	0.274	0.242	0.133	0.135	0.115
	NDVI	0.186	0.387	0.233	0.463	0.632
	SAVI	0.203	0.378	0.210	0.398	0.516
	LAI	0.21	0.70	0.23	0.77	1.69
	Temperature (°C)	43.1	41.35	42.25	34.65	30.35
	Soil heat flux (W/m²)	116.0	111.1	108.2	92.6	73.7
	ET (mm/day)	0.24	0.27	0.32	0.36	0.55

By the end of this wet period, natural vegetation showed higher values of ET due to the ability of the roots in using soil moisture from deeper layers and in conserving this water. The natural vegetation (caatinga) converted large portions of the available energy into sensible heat flux (H), resulting in values for 1990 in the range 50–350 W/m^2. The sensible heat flux for September 2009 is lower with values in the range 40–320 W/m².

Figure 6 illustrates the general evaporation features estimated with SEBAL in the Brígida River basin on 16 June 1990 and 24 September 2009, and shows the location of each canopy cover and the spatial distribution map of daily ET of two days in the dry season and early wet season, respectively. Higher evaporation spots coincide with the locations of the dense canopy and bush land which retains more water. The effect of low soil moisture availability was strong during the dry season (June 1990), mainly in the days before taking of the satellite image. Small values of ET are perceived in the months of September and October (beginning of the rainy season) (Fig. 2). Pixels with ET lower than 1 mm/day occurred frequently during this condition. These pixels represent natural vegetation (caatinga). The distribution of ET in bush land and dense canopy was greater than bare soil, cropland and grassland. The ET values obtained with SEBAL algorithm were able to represent the low observed ET of the canopy.

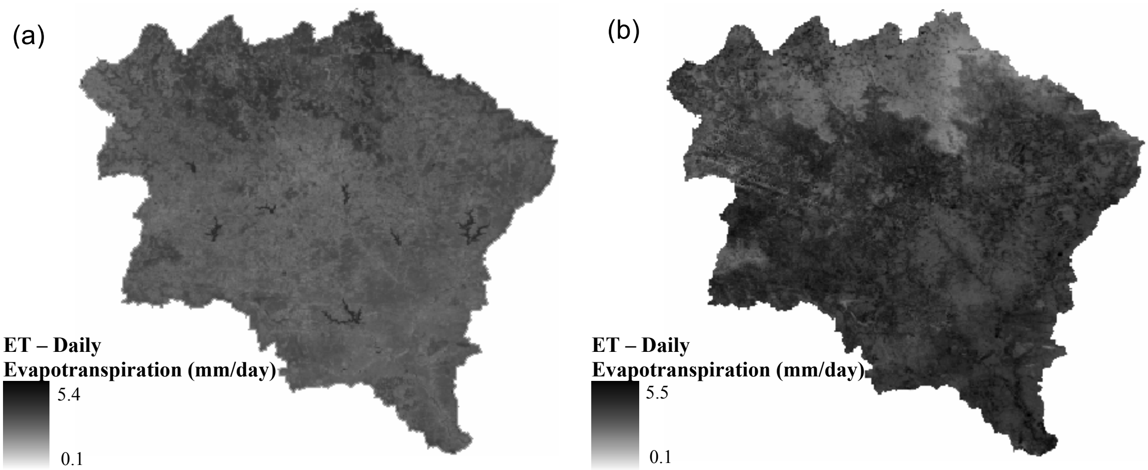

Fig. 6 Spatial distribution map of daily ET for study area to: (a) 16 June 1990, and (b) 24 September 2009, using TM Landsat 5 data, and location of main canopy covers selected in this study.

CONCLUSIONS

The main purpose of the present study was to test the application of the SEBAL algorithm using GIS and remote sensing techniques in a semi-arid basin in Pernambuco state, Brazil, in order to aid decision makers to manage water resource using data retrieved from satellite and meteorological stations. By comparing the results to point measurements, it was shown that the SEBAL method approaches the low ET prevailing at the time of image acquisitions. Furthermore, the method indicates a large spatial ET variability.

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