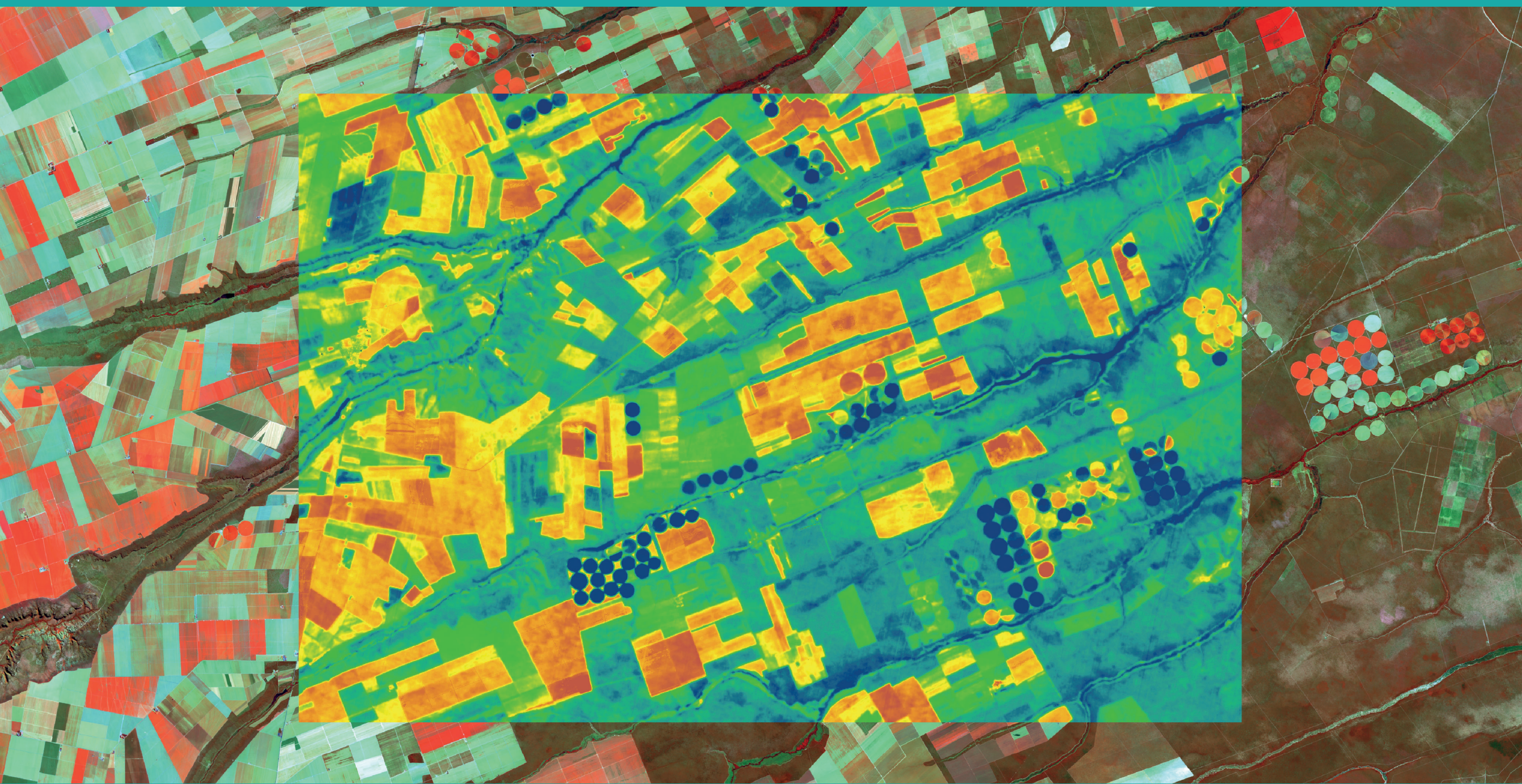
SSEBop BR

Evapotranspiration

Irrigation Atlas

MAPPING
ACTUAL EVAPOTRANSPIRATION



USING
REMOTE SENSING FOR BRAZIL

ANA
NATIONAL WATER AGENCY - BRAZIL

NATIONAL WATER AGENCY
MINISTRY OF REGIONAL DEVELOPMENT

MAPPING ACTUAL EVAPOTRANSPIRATION USING REMOTE SENSING FOR BRAZIL

BRASÍLIA - DF
ANA
2020

Setor Policial Sul, Área 5, Quadra 3, Blocos B, L, M e T.
CEP: 70610-200, Brasília – DF.
PABX: (61) 2109-5400 | (61) 2109-5252
Website: www.ana.gov.br

Illustrations, tables, and graphs with no credited source were prepared by ANA.

EDITORIAL STAFF
Editorial Supervision
Thiago Henriques Fontenelle
Daniel Assumpção Costa Ferreira

Revision of Originals
Daniel Assumpção Costa Ferreira
Marcus André Fuckner
Moisés Pereira Galvão Salgado

Graphic Design and Cover
Agência Nacional de Águas

Photographs
ANA Image Bank

Produced by
Agência Nacional de Águas
Agrosatélite Applied Geotechnology

Translate to English
Thiago Henriques Fontenelle

Cataloging at Source - CEDOC/ ANA's Library

A265e National Water Agency (Brazil).
Mapping actual evapotranspiration using remote sensing for Brazil / National Water Agency. -- Brasília: ANA, 2020.
41 p.: il.
1. Evapotranspiration 2. Remote Sensing. I. Title.
CDU 556.13:528.8(81)=111

Prepared by Fernanda Medeiros - CRB-1/1864

Technical Staff

National Water Agency

General Coordination
Sérgio Rodrigues Ayrimoraes Soares

Executive Coordination
Daniel Assumpção Costa Ferreira
Thiago Henriques Fontenelle
Marco Vinícius Castro Gonçalves

Contributors

National Water Agency
Adalberto Meller
Alexandre Lima de Figueiredo Teixeira
Juliana Dias Lopes
Le-Lyne Paes Leme Nunes Czeczko
Lígia Maria Nascimento de Araújo
Marcus André Fuckner
Marco José Melo Neves
Morris Scherer-Warren
Paulo Marcos Coutinho dos Santos
Raquel Rubstem Sado
Adriano Cesar Pereira de Paula (Intern)
Thais da Silva Dornelas (Consultant)

Federal University of Santa Maria Micrometeorology Laboratory
Débora Regina Roberti

Brazilian Agricultural Research Corporation
Lineu Neiva Rodrigues

United States Geological Survey
Gabriel Senay
Brian McCallum
Jesslyn Brown
MacKenzie Friedrichs (KBR-Contractor)
Bruce Worstell (KBR-Contractor)

Agrosatélite Applied Geotechnology
Moisés Pereira Galvão Salgado
Marciano Saraiva
Bernardo Friedrich Theodor Rudorff
Daniel Alves de Aguiar

Plantations and rural roads in Ribeirão Preto (São Paulo State)
Raylton Alves / ANA Image Bank

CONTENTS

INTRODUCTION

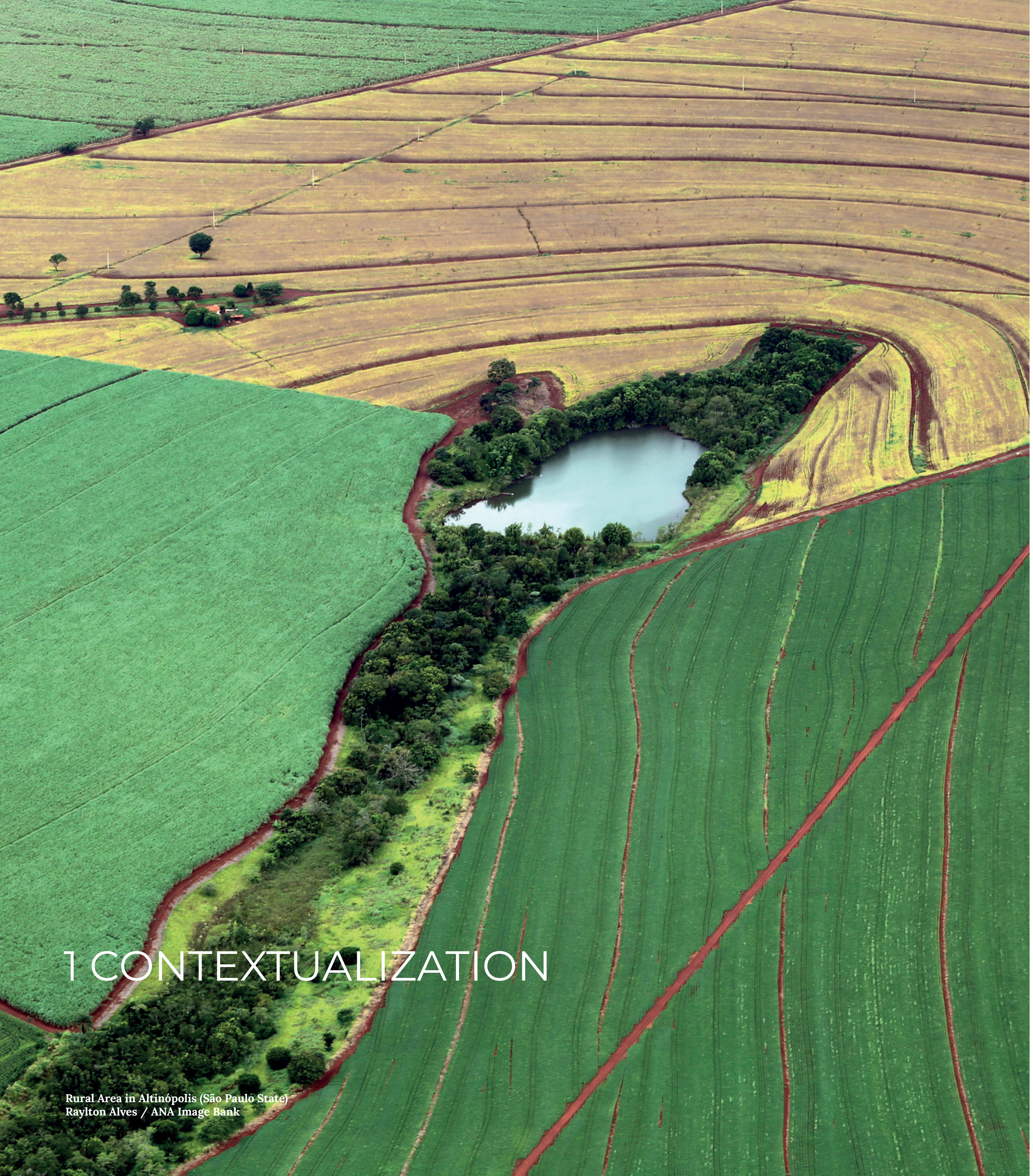
Riparian forest, pastures and plantations on the banks of the Uberaba river in Uberaba (Minas Gerais State)
Raylton Alves / ANA Image Bank

Irrigated agriculture is the largest and most dynamic water user sector in Brazil and worldwide, which poses several challenges for water resources management. The National Water Agency - ANA and its partners, such as the National Company of Supplying (Conab) and the Brazilian Agricultural Research Corporation (Embrapa), have been making efforts to identify equipped areas for irrigation and monitor the effective irrigation throughout the years in order to improve water use estimates, which have several applications, remarkably in water resources planning and management.

Water use estimates in irrigation is generally based on water balance in irrigated areas, requiring information on climate, crops and irrigation systems. In the case of sugarcane and flooded rice, ANA adopts complementary calculation methods to simulate crop management specificities. Water use indirect estimation methods have good accuracy and are also adopted on rural property scale for equipment and infrastructure sizing.

With computational and geotechnology development, remote sensing-based applications have been enhanced to reduce uncertainties associated with large number of variables and simplifications required by traditional models. In this context, models based on remote sensing data, of varying complexity, have stood out for their good results in several applications in the world. Since 2015 ANA has been working with the *United States Geological Survey* (USGS) on the implementation and parameterization of the Operational Simplified Surface Energy Balance (SSEBop) model in Brazil, adapting it to our morphoclimatic reality.

With recent advances in cloud data processing and interface development, ANA presents in the publication *Mapping Actual Evapotranspiration using Remote Sensing for Brazil* an important record of the methodology, the web app and its applications in Brazil. Evapotranspiration estimates for any point in the Brazilian territory are available online through the SSEBop BR Web Application, available on the National Water Resources Information System website (www.snirh.gov.br > Water Uses).



1 CONTEXTUALIZATION

Rural Area in Altinópolis (São Paulo State)
Raylton Alves / ANA Image Bank

Evapotranspiration comprises both evaporation of water from soil and vegetation and transpiration of plants. In other words, it represents the total water transferred from the earth's surface to the atmosphere. In Brazil, about 75% of precipitation returns to atmosphere through evapotranspiration, highlighting its importance in the hydrological cycle. However, due to the gaseous state of water, it is hard to estimate evapotranspiration from direct methods and even to measure it at field level. So, only indirect methods such as remote sensing are practical for large scale mapping.

Several factors influence evapotranspiration, including climate, soil type, land use and water management. Radiation, temperature, relative humidity and wind are the main interfering climatic variables. Different land use patterns such as livestock, agricultural and protected/natural areas are associated with different land cover, establishing different evaporation and transpiration patterns, intertwined by different soil types and their respective water storage capacities. Artificial water application (irrigation) and practices that facilitate or hinder soil water storage are also key factors in determining the volume of evapotranspirated water. Crop variety, its spacing and orientation also influence evapotranspiration process in agricultural areas.

So many intervening factors bring even more complexity to the evapotranspiration estimate. On the other hand, incresing availability and quality of free remote sensing products, coupled with technological developments in data processing and analysis, have enabled the development of effective computational tools for mapping real evapotranspiration (ETa) at different spatial scales (local, regional and global).

Actual evapotranspiration (ETa) can be measured by means of lysimeters, flux towers (eddy covariance and scintillometers) or with evaporation pots and stations (Bowen ratio). These options require substantial investment and effort and well-trained staff, and sampling will be spatial and temporal limited.

A simple technique for estimating ETa is with the crop coefficient (Kc) (Allen et al., 1998), widely used because of its simplicity and the availability of reference data (ETa = ETr x Kc). This method requires calculation of reference evapotranspiration (ETo or ETr) - usually through data from climatological stations. There is, however, great difficulty in determining regional coefficients sampled according to the type and stage of crop development, as well as in identifying the crop and stage in satellite images for the application of the most appropriate Kc.

Considering the computational and geotechnology developments, since the 1970s several approaches have been developed to estimate ETa based on field and remote sensing data (Li et al., 2009) to cover large areas in short time periods. More complex models are inspired by the surface energy balance, where the available energy from short and long wave radiation is balanced by terrestrial surface heating fluxes and water phase changes, such as the ETa (McShane et al., 2017). This way, ETa is estimated through total or partial solution of the surface energy balance and the application of analytical approaches based on physical models.

In short, energy-balance models are based on the assumption that in ETa process part of the available energy is used to vaporize water, and this energy and ETa flows can be estimated from remote sensing data and surface weather stations data.

The following models stand out in the development of the energy-balance approach to estimate ETa: *Surface Energy Balance Index* (SEBI) (Menenti & Choudhury, 1993), *Surface Energy Balance Algorithms for Land* (SEBAL) (Bastiaanssen et al., 1998), *Atmosphere-Land Exchange Inverse* (ALEXI) (Mecikalski et al., 1999), *Two-Source Model* (TSM) (Norman et al., 1995), *Surface Energy Balance System* (SEBS) (Su, 2002), *Mapping Evapotranspiration at High Resolution and with Internalized Calibration* (METRIC) (Allen et al., 2007) and *Operational Simplified Surface Energy Balance* (SSEBop) (Senay et al., 2007; 2013; 2016; 2017; 2018). Some publications have reviewed these and other ETa estimation models and methods (Allen et al., 2011; Glenn et al., 2011; Gowda et al., 2007; Kalma et al., 2008; McShane et al., 2017).

The SSEBop model has been applied by the *United States Geological Survey* (USGS) to estimate irrigation water use in the United States and has been tested and adapted by ANA since 2015 for water use estimates in watersheds with large irrigated areas in Brazil. Compared to models like METRIC, SSEBop can be considered a simpler alternative because it requires fewer input data and its parameterization is more objective, facilitating its implementation and without substantial loss of accuracy in estimating actual evapotranspiration (McShane et al., 2017).

In irrigated areas, ETa is useful for estimating water used by plants, not differentiating contributions from different sources (rain, soil storage and irrigation itself). Adding data measured or estimated from what is supplemented by natural sources (rain and soil), it is possible to estimate the portion artificially applied through irrigation. In regions with well-defined dry-season, estimates are facilitated by both low cloud cover in satellite imagery and low or absent rainfall contribution to crops growth.

In the first edition of the *Irrigation Atlas: water use in irrigated agriculture*, launched in 2017, ANA pointed to the modeling of evapotranspiration with SSEBop as an important line of action in the expansion of knowledge about water use by irrigated agriculture in Brazil (Figure 1). At the present publication, the advances made in this theme will be pointed out.

Figure 1 shows a sample of a scene with evapotranspiration calculated in western Bahia, on two days of the year (in May and August), showing high evapotranspiration in several central pivots, highlighting the potential consumption by irrigation (dark green color). Areas with low evapotranspiration (yellowish and reddish colors) show unplanted agricultural areas (bare or semi bare soil) as well as idle (unplanted) or quite recently planted pivots.

It should be noted that although SSEBop model has been operationalized by ANA in Brazil with a focus on irrigated area identification and water use estimate, evapotranspiration is calculated for any target, with applicability in other topics, such as: water balance at watershed scale, drought monitoring and rainfed agricultural management.

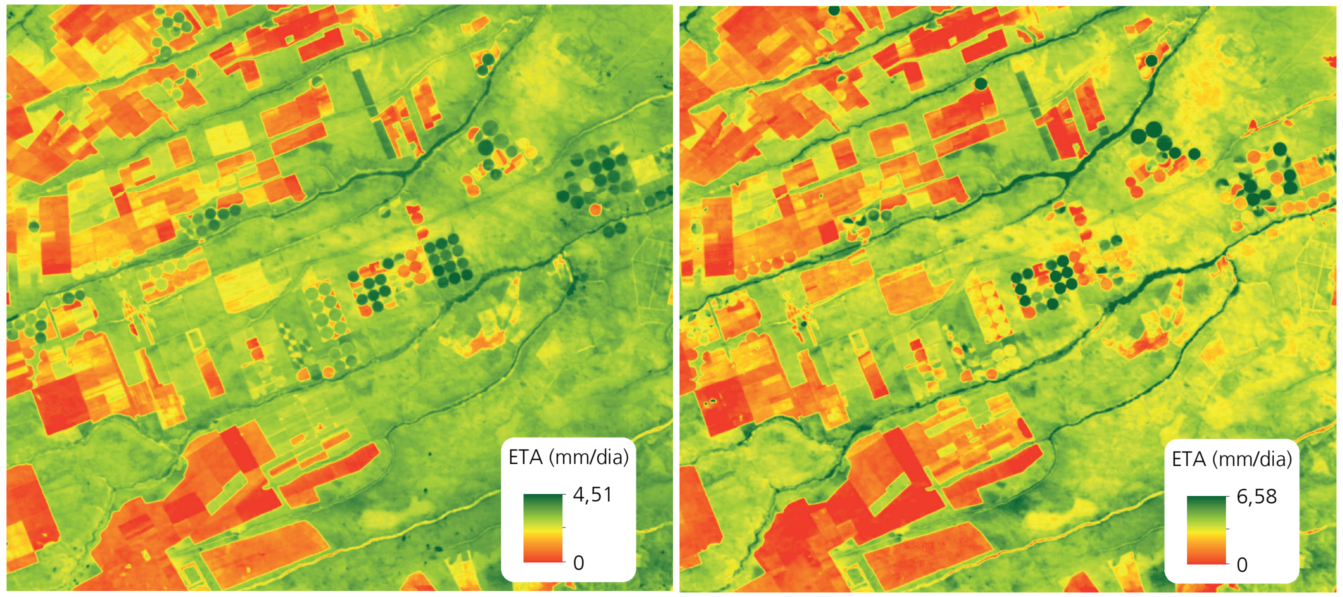
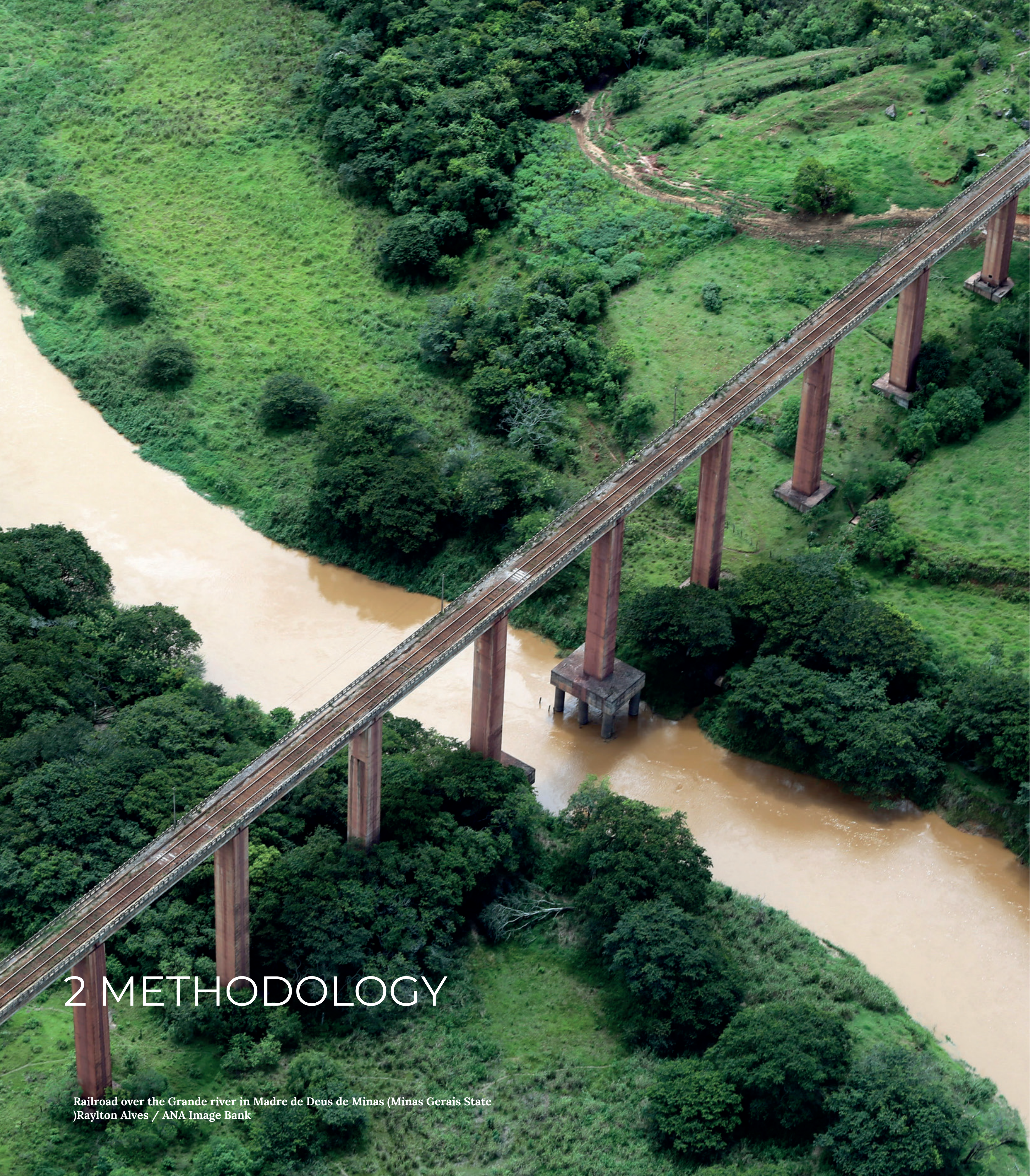


Figure 1. Estimated actual evapotranspiration (ETa) in an area of western Bahia.
Note: Images from May 20 and August 23, 2013, respectively.



2 METHODOLOGY

Railroad over the Grande river in Madre de Deus de Minas (Minas Gerais State
)Raylton Alves / ANA Image Bank

Actual evapotranspiration estimation (ETa) models that perform the total or partial solution of surface energy balance apply the classical energy balance equation (Eq. 1), where latent heat flow - LE (energy consumed by evapotranspiration) is calculated as the residual difference between the net surface radiation balance - Rn, the losses due to the sensible heat flux - H (energy consumed to heat the air) and the ground heat flux - G (energy stored / transferred to the air, soil and vegetation).

$$LE = Rn - G - H \quad \text{(Eq. 1)}$$

where:

LE = latent heat flow (energy consumed by evapotranspiration – $W.m^{-2}$);

Rn = surface net radiation ($W.m^{-2}$);

G = ground heat flux (energy stored in soil and vegetation – $W.m^{-2}$); and

H = sensitive heat flow (energy consumed to heat air – $W.m^{-2}$).

This approach has been successfully applied by several researchers to estimate water use in irrigated areas (Senay et al., 2007), demonstrating good results in many conducted studies. On the other hand, using the complete energy balance equation (Eq. 1) requires a lot of high-quality input data, specific calibration and trained specialists to solve the equations, which makes the automation and the model application difficult for broader scale analysis (Gowda, et al., 2007; Santos et al., 2008).

The SSEBop model uses a simplified version of the energy balance equation for ETa estimation, maintaining and expanding the main assumptions described in SEBAL (Bastiaanssen et al., 1998) and METRIC (Allen et al., 2007) models. Both SEBAL and METRIC assume that the temperature difference between earth's surface and air (near-surface temperature difference) varies linearly with the earth's surface temperature. Both models also establish this relationship anchored in the concept of hot pixel and cold pixel. The hot pixel should be sampled on a bare, dry soil surface; and the cold pixel in a well-vegetated, moist area. Thus, these methods are based on the linear relationship between the near-surface air temperature difference and surface temperature to estimate the sensible heat flux (H), which varies as a function of the near-surface temperature difference, assuming that in the hot pixel there is no latent heat flux (ETa = 0) and in the cold pixel the ETa value reaches its maximum (ETa near potential evapotranspiration).

SSEBop configuration is based on the Simplified Surface Energy Balance (SSEB) approach (Senay et al., 2007) with unique parameterization for operational applications (Senay et al., 2013). Initially, SSEB extended the premise adopted by METRIC and SEBAL assuming that latent heat flow (real evapotranspiration) also varies linearly between hot and cold pixels (Senay et al., 2007). This assumption assumes that the temperature difference between soil surface and air is linearly related to soil moisture (Sadler et al. 2000). Thus, the SSEB authors argue that ETa can be estimated by the near-surface temperature difference, which in turn can be estimated from the surface temperatures of a hot pixel and a cold pixel of the study area. That is, while in the hot pixel, sampled in an area of exposed and dry soil, it is expected to be close to zero ETa, in the well vegetated and humid pixel there will be a maximum ETa. In the other pixels of the study area the ETa will vary with the surface temperature in proportion to the temperature difference of the hot and cold pixels (Senay et al., 2007).

Although in the SSEB model the amount of input data and expertise required for its correct implementation has been drastically reduced compared to models using the complete energy balance equation (Eq.1), it still requires a different parameterization for each hydroclimatic typology, where the hot and cold pixel values would be comparable, which would normally not exceed an area of 200 km x 200 km. Aware that this parameterization makes the automation process very difficult, the authors of SSEB simplified it by launching the SSEBop model (Senay et al., 2013).

SSEBop represented a breakthrough in automation of ETa estimation. Through boundary conditions based on energy balance, the temperature difference between hot and cold reference pixels is predefined for each pixel (Senay et al., 2013). The Satellite Psychrometric Approach (Senay, 2018) explains the SSEBop model more effectively than the energy typical balance principle because SSEBop does not solve all terms of the surface energy balance such as sensible and ground-heat fluxes.

SSEBop model estimates the ETa in mm per day, according to Equation 2. The evapotranspiration fraction (ETf, ranging from 0 to ~ 1) is based on air temperature (Ta) and surface temperature data (Ts). Ts is obtained through remote sensing satellites that have thermal band such as MODIS and Landsat. ETf is then multiplied by the reference evapotranspiration (ETr), usually estimated by the Penman-Monteith method for an alfalfa surface in the region of interest. Eventually, the ETo (grass reference) may be adjusted by a scalar factor (k) to a maximum reference evapotranspiration level of an aerodynamically rougher crop such as alfalfa (ETr). The reference evapotranspiration (alfalfa) is generally 20 to 40% higher than potential evapotranspiration from grass, varying according to humidity and wind speed (Senay et al., 2013). It should be noted that SSEBop BR has the option of using the ETo (grass) compiled by Xavier et al. (2016), available for the period between 1980 and 2017, with the adjustment factor (Kr) that matches the values for ETr (ETr = ETo x Kr). ETr is directly calculated in the oth-er meteorological datasets available at SSEBop BR (GLDAS and CFSv2).

$$ET_a = ET_f \times ET_r \qquad \text{(Eq. 2)}$$

In Equation 2, the evapotranspiration fraction (ETf) is calculated according to Equation 3:

$$ET_f = \frac{Th - Ts}{dT} = \frac{Th - Ts}{Th - Tc} \qquad \text{(Eq. 3)}$$

where:

ETf is estimated on a given day of the year, indicating the surface humidity condition;

Th is the estimated hot/dry pixel temperature at the same pixel and date;

Tc is the estimated cold/wet pixel value also at the same pixel and date;

Ts is the observed surface temperature, obtained by satellite images in the pixel; and

dT is the pre-defined temperature difference between Th and Tc for each pixel under analysis.

The cold / wet pixel (Tc) reference value is calculated from the maximum temperature (Ta) multiplied by a correction factor (c-factor) that correlates Ta to Ts in pixels located in well-vegetated regions. Typically, c-factor ranges from 0.96 to 0.99, as described in the SSEBop model release article (Senay et al., 2013) that also detail the procedures to be performed to establish c-factor, like NDVI[1] range for instance. The reference value for the hot pixel (Th) is computed by summing Tc and dT.

The dT value for each pixel is defined a priori and is calculated under clear sky conditions (without cloud cover), varying according to location and day of year, but it is considered that it does not change from one year to the next. Equation 4 shows the dT calculation formula. Multiplication factors are applied to compatibility of the measurement units of energy, mass, volume and time (Senay et al., 2016).

$$dT = \frac{Rn * rah}{pa * Cp} \qquad \text{(Eq. 4)}$$

where:

Rn ($J.m^{-2}.s^{-1}$) is the average net radiation reaching the earth's surface under clear sky condition;

rah is the aerodynamic resistance to heat transfer from a dry, bare surface (usually 110 $s.m^{-1}$);

pa is the air density (kg/m^3) estimated as a fuction of air temperature and air pressure; and

Cp is the air specific heat at a constant pressure (1.013 $kJ\ kg^{-1} K^{-1}$).

By algebraically rearranging Equations 2, 3, and 4, actual evapotranspiration (ETa) can be calculated as Equation 5:

$$ET_a = \frac{pa * Cp}{Rn * rah} (Th - Ts) * k * ETr \qquad \text{(Eq . 5)}$$

More detailed references about SSEBop can be found in Senay et al. (2013), Senay et al. (2017) and Senay (2018).

[1]Note: the NDVI - Normalized Difference Vegetation Index - ranges from -1 to 1, where values below zero represent water, between 0 and 0.1 exposed soil, and values above 0.1 vegetated area, growing proportionally to the maximum. 1 as a function of leaf biomass and vegetative vigor.

Figure 2 illustrates the conceptual diagram of SSEBop model for evapotranspiration estimates on Landsat 5, 7 and 8 satellite images in Brazil (images from 1984 to the present). This implementation made by ANA with USGS support is called SSEBop BR. Table 1 summarizes the input data required by SSEBop model and its sources of information for Brazil. Table 2 details the parameters and pixel sampling definition for the correction factor calculation (c-factor).

For its operationalization, initially, the model was implemented in a GIS-Desktop environment. However, it was decided to implement SSEBop BR on the Google Earth Engine platform (GEE) due to its processing capacity, availability of data from remote sensors and meteorological models, as well as the possibility of making results available widely and interactively. The user-friendly interface provided on the National Water Resources Information System (SNIRH) portal allows users to produce ETa estimates easily and without any software installed or GIS experience.

SSEBop Model Methodology

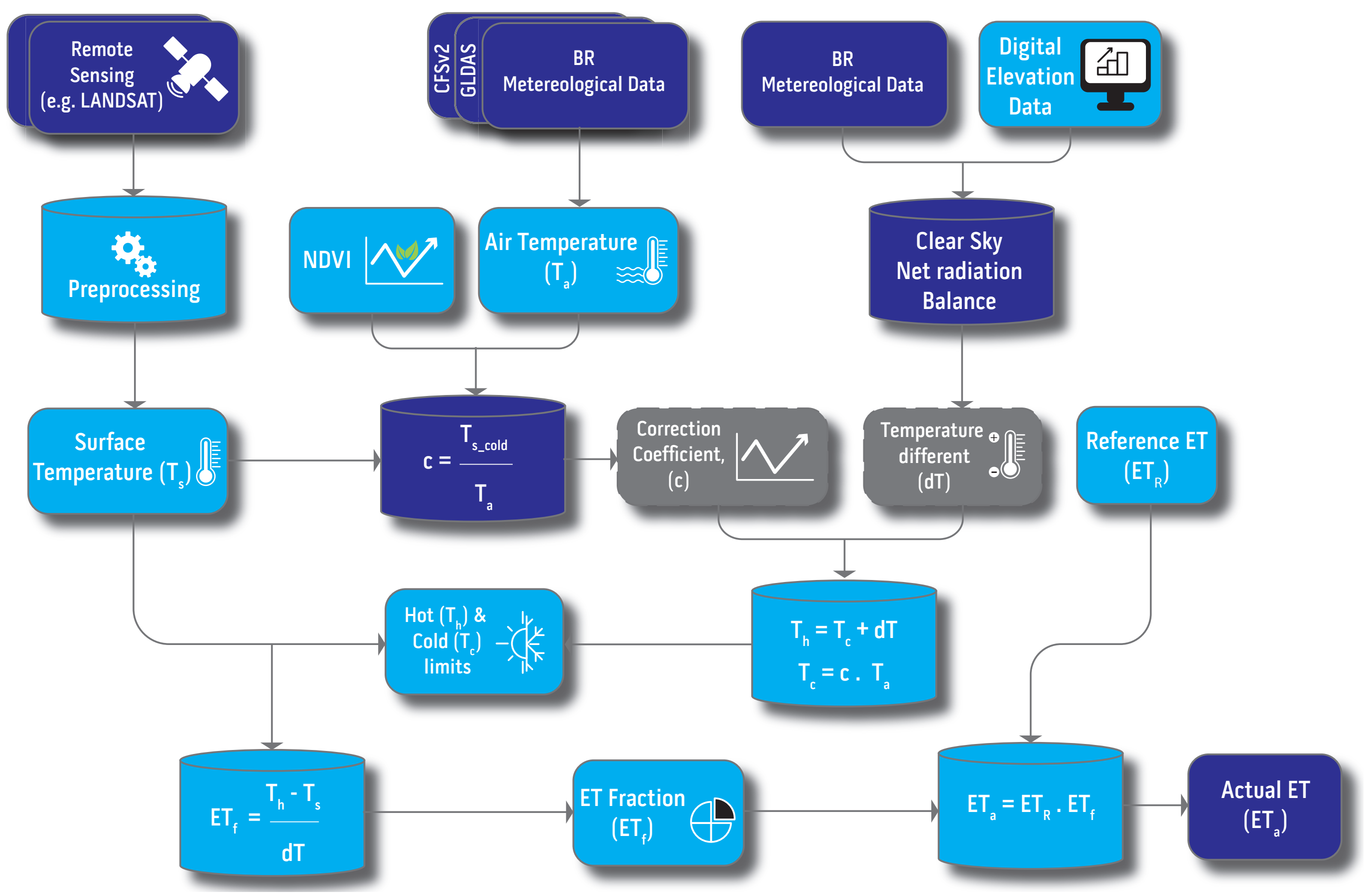


Figure 2. Steps for calculating actual evapotranspiration (Eta) with SSEBop BR.

Source: adapted from Senay et al. (2016).

Table 1. Summary of data types, sources and purpose of parameterization and operation of the SSEBop BR

DATASET	SYMBOL	SOURCE	PURPOSE
Elevation	z	SRTM	Air pressure
c factor: Temperature correction coef-ficient	c	Meteorological data[1]	Tc
Land surface temperature	Ts	Landsat	ETf, ETa
Maximum Air temperature	Ta	Meteorological data[1]	Rn, Th,Tc, dT
Temperature difference	dT	Model	dT
Clear-sky net radiation	Rn	Model	dT
Reference ET	ETr	Meteorological data[1]	ETa
Aerodynamic resistance	rah	Model	dT
Albedo	α	Landsat	Ts
Normalized Difference Vegetation Index	NDVI	Landsat	c, Tc

[1] Note: the available weather data sets are:: a) Xavier et al. (2016), where rasters of ~27km x ~27km are derived from the Brazilian national hydrometeorological network; b) *Global Land Data Assimilation System* (GLDAS 2.1); c) *National Centers for Environmental Prediction Climate Forecast System* (CFSv2).

Table 2. Constraining parameters for producing c-factor by filtering the T_{corr}

DATA	PARAMETERS	REMARK
NDVI	0.75 ≤ NDVI ≤ 1.0	Healthy "greenest" vegetation
Ts	> 270 K	Mask out cloud and snow pixels
QA band	≥ 500 clear pixels	Minimum sample size. If <500 proper pixels in the scene, the scene's average historical value is used.
Tdiff	0 K ≤ (Ta – Ts) ≤ 30 K	Remove unreal temperature differences
Tcorr	Ta / Ts	Pixel-based preliminary c factor over well-vegetated surfaces, meeting above criteria
c-factor	Mean Tcorr	c-factor based on greenest and wettest/coldest vegetation

Notes: Landsat pixels that meet all listed criteria are used for c-factor calculation. Some parameters were modified for the use of SSEBop in Brazilian territory and differ from the values published in the mentioned literature (Senay et al. 2017). These values are shown in Table 2.

3 SSEBop BR WEB APPLICATION

Rural area in the Paranapanema river basin
Raylton Alves/ ANA Image Bank

3.1 INSTRUCTIONS AND DEFINITIONS

The SSEBop BR app, available at www.snirh.gov.br or http://bit.ly/ssebopbr, processes individual scenes from Landsat 5, 7, and 8 satellites, from any period from 1984 to the present, and for nearly all areas of the globe. Initially, the application of the model is restricted to the Brazilian territory.

Grass and alfalfa reference (ETo, ETr) is independently calculated using available weather data. The SSEBop app provides three data sources for ETr and ETo calculation: Brazilian station network (consolidated and gridded by Xavier et al., 2016), GLDAS 2.1 (Rodell et al., 2004) or CFSV2 (Saha et al, 2011). ETr is calculated using the “alfalfa reference” according to the ASCE standardized Penman-Monteith equation (Walter et al., 2000).

As mentioned before, the satellite psychrometric approach (Senay 2018) explains the SSEBop model more effectively than typical energy balance principle because SSEBop does not solve all terms of the surface energy balance such as sensible and ground-heat fluxes. The model itself estimates ET fraction (ETf), that is similar to the traditionally used ‘crop coefficient’ (ETf = ETa/ETr). So, ETa is a multiplication of ETf by ETr.

SSEBop BR app provides a friendly interface for actual evapotranspiration (ETa) estimates. Users must specify -begin and -end dates to search in the date window and then move Google Maps into the area of interest. When the ‘search for images in the center of map’ button is pressed, the SSEBop app will search the Google Earth Engine Data Catalog archive for those Landsat images within the date range and path/row in the center of map. For areas that are covered by two paths, images from both paths will be presented. SSEBop BR app will then provide a list of images for the location and allow users to select one image to process. SSEBop BR app processes one image (scene) at a time. The list of images available includes an assessment of percent cloud cover for the entire scene as determined by USGS EROS data center (Figure 3).

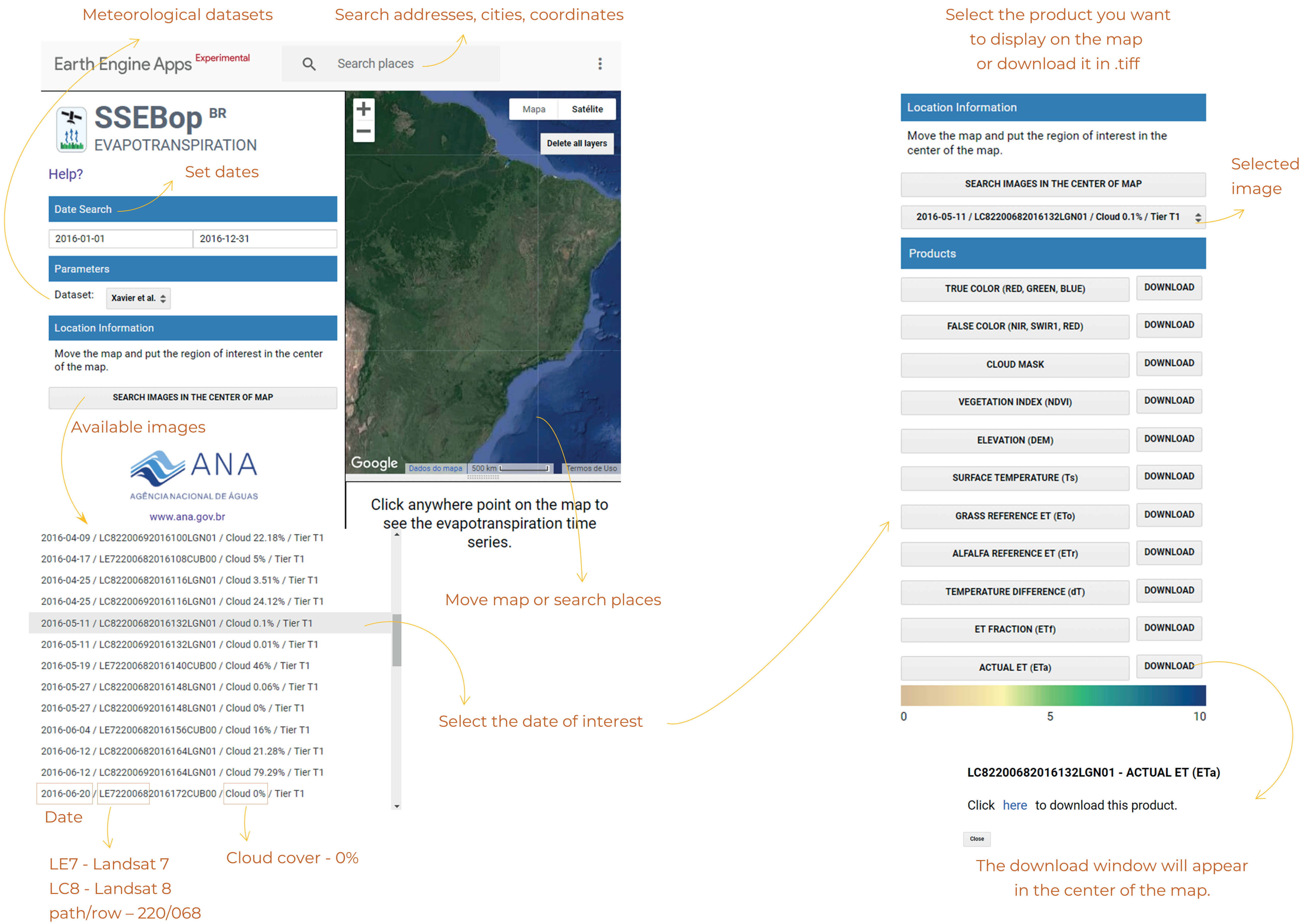


Figure 4. SSEBop BR app use instructions (www.bit.ly/ssebopbr).

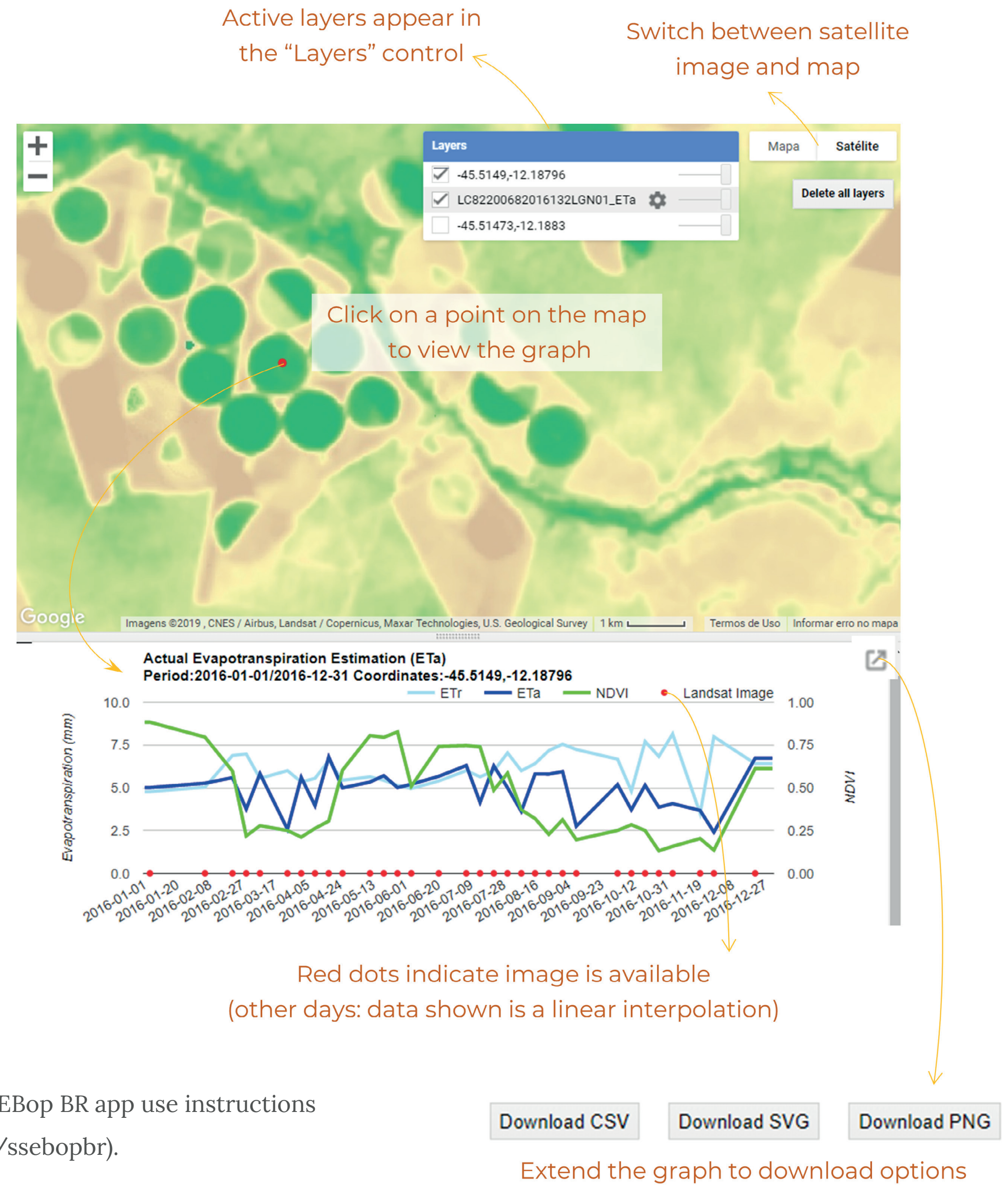


Figure 4. SSEBop BR app use instructions (www.bit.ly/ssebopbr).

Once an image has been selected, SSEBop app will present a list of data layers that can be displayed in the map window. ET fraction (ETf) and Actual ET (ETa) images can be downloaded as GeoTIFF files using hot links on the SSEBop app site ('download' buttons).

In addition to visualization and download of all input model data layers and output resulted layers over desired period, users can also left click on a base map and SSEBop BR will generate a time series graphic with the variation of ETr, Eta and NDVI along that period (Figure 4). Clicking on the small arrow located on right top corner of this graphic users will also have access to .csv table of data used to generate it and download the .png/svg picture of the graphic itself.

DEFINITIONS

TRUE COLOR (RED, GREEN, BLUE)– This is a color composite of the red, green and blue bands of the Landsat image.

FALSE COLOR (NIR, SWIR1, RED) – This is a color composite of Landsat 5 and 7 bands 4, 5 and 3. For Landsat 8, it is bands 5, 6, 4.

CLOUD MASK - Cloud mask based on Landsat Quality Assessment band.

VEGETATION INDEX (NDVI) – Normalized Difference Vegetation Index, calculated from the Near Infrared (NIR) band and red band using at-surface reflectance.

ELEVATION (DEM) – Digital Elevation Model in meters. We use the 30m SRTM.

SURFACE TEMPERATURE (Ts) – This is the land surface temperature derived from the Landsat Collection 1 Tier 1 images. The native resolution of Landsat 5 is 120 m, of Landsat 7 is 60 m, and of Landsat 8 is 100 m. These are all resampled to 30 m by USGS-EROS using cubic convolution. Units are in Kelvin (K).

GRASS REFERENCE ET (ETo) – This is the standardized ASCE reference ET for the daily clipped, cool season grass Penman-Monteith reference equation (Walter et al., 2000, Allen et al., 1998) and represents an average maximum ET rate for clipped grass. ETo tends to be 20 to 40% lower than alfalfa reference ETr. Units are in millimeters (mm).

ALFALFA REFERENCE ET (ETr) – This is the standardized ASCE reference ET for the daily tall alfalfa Penman-Monteith reference equation (Walter et al., 2000) and represents a near maximum ET rate. ETr tends to be 20 to 40% higher than grass reference ETo. Units are in millimeters (mm).

TEMPERATURE DIFFERENCE (dT) – This defines the temperature difference (dT) in K between the "hot" (bare areas) and "cold" (well vegetated) reference values for each pixel. The cold limit temperature is expected to be equal to the air temperature at the canopy level, making dT the difference between surface and air temperature over the bare/dry surface. The novelty in the SSEBop model is that dT is predefined for a given pixel, unlike the original SSEB formulation or similar energy balance models that use a set of reference hot and cold pixel pairs applicable for a uniform hydro-climatic region.

ET FRACTION (ETf) – This is the "fraction of alfalfa reference ET" (ETr) estimated by SSEBop model and is similar to the alfalfa reference-based crop coefficient under observed conditions. ETf generally should vary from 0 to 1.05.

ACTUAL ET (ETa) – Actual ET (ETa) is estimated as a fraction of the Alfalfa Reference ET (ETr by default). It is calculated using the ET fraction times the Referece ET. ETa = ETf * ETr. Units are in millimeters (mm).

3.2 FREQUENTLY ASKED QUESTIONS (FAQ)

The following questions and their answers seek to clarify the main questions when handling the SSEBop BR Web App.

Why aren't my downloads working?

There are two common situations. If the download doesn't even start, your pop-up blocker may be blocking the download. Simply turn it off and try again. If you get a downloaded image but it won't open, or is corrupted, then your internet connection was likely interrupted during the download. We are researching more stable methods for providing downloads.

Can more than one Landsat scene and date be processed at the same time?

No. Each date and scene are processed independently. They can be downloaded and stitched together in image processing applications.

What are the differences between available meteorological datasets?

Xavier dataset is based on meteorological stations of Brazil data interpolation with a pixel size of 0.25 x 0.25 arc degrees and comprises the period from 1985 to 2017. Xavier median is the daily median based on the period from 2005 to 2017. CFSV2 is a daily aggregation based on a fully coupled model representing the interaction between the Earth's atmosphere, oceans, land, and sea ice with a pixel size of 0.2 x 0.2 arc degrees and comprises the period from 1979 to present. GLDAS ingests satellite and ground-based observational data products to generates optimal fields of land surface states and fluxes using advanced land surface modeling and data assimilation techniques. It has a pixel size of 0.25 x 0.25 arc degrees and comprises the period from 2000 to present.

How was dT estimated?

It uses a daily average from 1980 to 2013 based on the weather data set for Brazil (Xavier et al, 2016) under clear sky conditions (Senay, 2013).

What do I do with an ETf image once I download it?

You can use the ETf image as is to show areas of high and low relative ET. These can be useful to assessing areas of water stress, areas of irrigation, and spatial distribution of ET. The ETf image can be 'colorized' using image processing systems. The ETf images can be used to develop crop coefficient curves and to derive estimates of soil moisture. The crop coefficient from this exercise could be lower than published values which are determined under optimum agronomic condition, reflecting type and stage of crop but not under stress conditions. If total (integrated) ET over a time period, such as one month or one growing period or one year is desired, then one will need to process multiple images and then conduct a time-integration. The daily ET values are then summed over the period of interest. ETf is also useful if you want to estimate ETa with ETr or ETo data from other sources of information.

What are the no-data areas on the images?

These areas were masked by cloud and shadow filter applied to Landsat images. ETa can not be estimated for pixels under cloud / shadow influence.

What if the SSEBop app does not successfully produce an ET image (it 'times out' and gives a 'Something went wrong on the server. Please try again.' Message)?

This may be a bug or the application may be under maintenance. If after several attempts you still receive this message, try again after a period of 24 hours.

How is SSEBop model calibration for temperature correction (c-factor) performed?

SSEBop c-factor is uniquely calculated for each Landsat scene from well-watered/vegetated pixels. This temperature correction component is based on a ratio of maximum air temperature and land surface temperature that has passed through several conditions such as NDVI limits. Users are advised to refer to general methodology (Senay et al., 2017) and the specific Brazil implementation in Table 2 of this document.

How should I cite the use of the SSEBop app and data downloaded from this application?

You should cite this document. Full reference: National Water Agency (BRAZIL). ***Mapping actual evapotranspiration using remote sensing for Brazil***. Brasília: ANA, 2020. Accessible at www.snirh.gov.br > Uses of Water.

3.3 ANALYSIS

SSEBop BR represents well the spatiotemporal variability of evapotranspiration and its values are consistent with field-measured data and other indirect estimates, as detailed in the following discussion. Other studies in Brazil that implemented SSEBop also stand similar conclusions (Lopes et al., 2019; Paula et al., 2019).

Actual evapotranspiration estimates have several applications - from local scale crop coefficients to basin scale water balance. Drought monitoring, agricultural management and surface and underground hydrological modeling are other important usual applications.

For water resources management, in addition to hydrological modeling, an important application of these estimates is for irrigated areas identification, water use estimation and its monitoring.

An exploratory evaluation was conducted in western Bahia, Brazil, at Grande and Correntes rivers basins - the largest irrigated area by center pivots in Brazil (ANA, 2019). This region is the most important producer of MATOPIBA - wide agriculture expansion area between the states of Maranhão, Tocantins, Piauí and Bahia. This region is characterized by extensive rainfed areas and also by strong irrigation using center pivots. Farmers concentrate their activities in periods of higher water supply, using irrigation as a supplementary source of water. This way, many equipments are inactive during the dry season (May to September), especially at its peak (July to September). The percentage of activity/inactivity of pivots is, however, quite variable, being influenced by the food market, public policies and water availability, among other factors.

Evapotranspiration (ETa) in western Bahia was estimated between May and September of 2013 (dry season). This year, average rainfall in the basin was close to zero (9, 3, 0, 0, and 6 mm, by month, respectively). That way, precipitation was considered zero, and the values consumed by evapotranspiration (ETa) were fully due to irrigation.

Figure 5 shows in detail the variation of ETa, temperature (LST) and NDVI in two pivots at two seasons - before planting (05/19/2013) and with irrigated crop (09/24/2013). As expected, there is a relationship between the variables - the highest NDVI values relates to low surface temperature (LST) high actual evapotranspiration. It is also observed in May that in the lowest NDVI value the surface temperature is low and ETa is higher, which corresponds to the presence of soil moisture, possibly due to pre-seeding irrigation.

In order to evaluate SSEBop ETa estimates, monthly ETa estimation were compared with the average monthly irrigation grant flows in the region and indirect estimates based on water balance in irrigated areas (ANA, 2019), all expressed in l / s.ha, as shown in Figure 6. These calculations were performed for the total area irrigated by 1,275 center pivots, which total about 137,000 hectares.

From the universe of 1,275 central pivots in the irrigated agricultural areas, those with monthly average NDVI greater than 0.5 in each month, from May to September, were selected for analysis, aiming to select those most likely to be planted. The same graph at Figure 6 also shows the average NDVI values of the selected pivots and the respective number of pivots. There is a progressive reduction of potentially active pivots in the region (NDVI> 0.5), from 50% of the total in May to 25% in September, 2013.

Most of water users has to have a grant to operate in Brazil (water withdrawals authorization given by

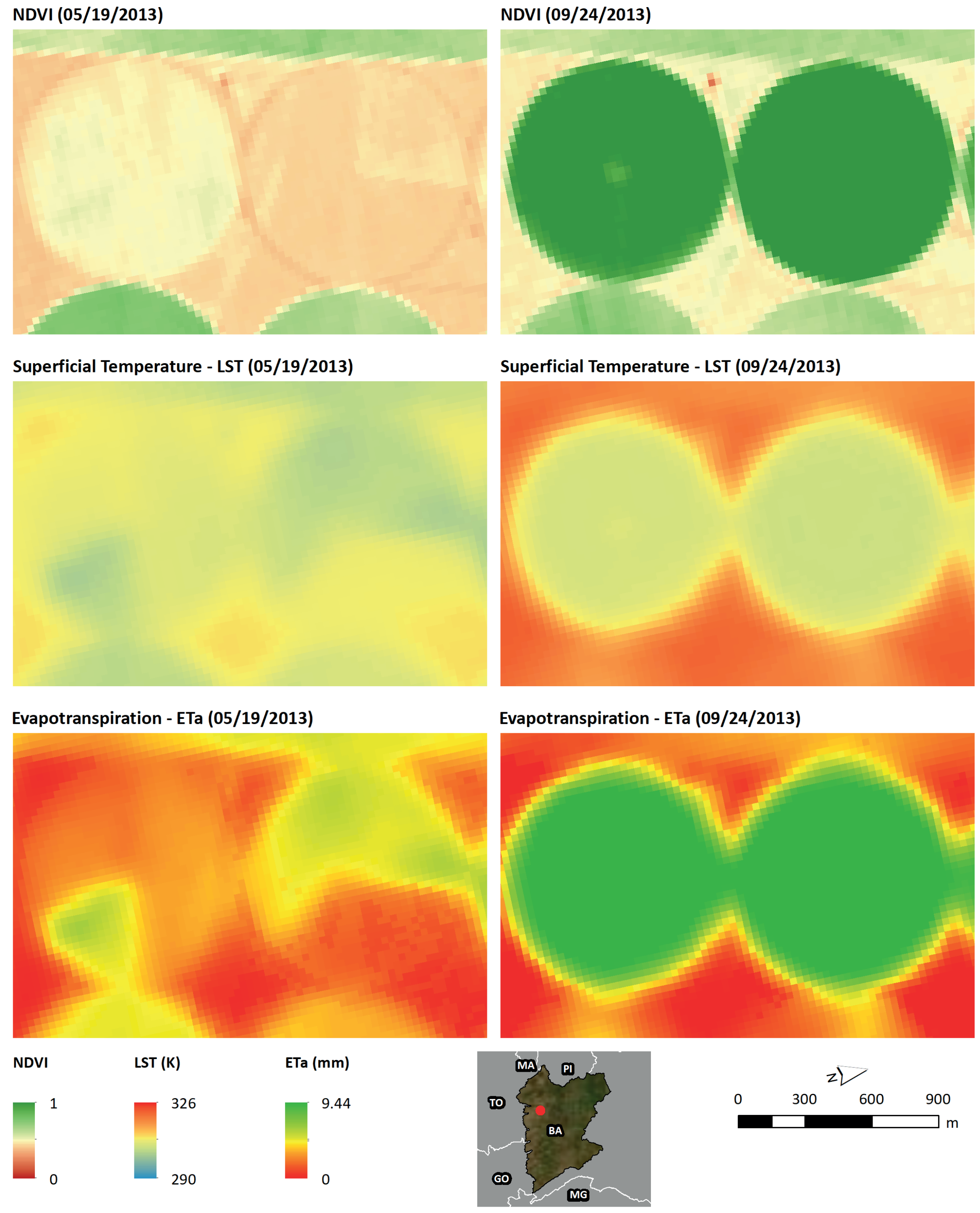


Figure 5. Comparison of ETa, NDVI and LST in pivot area in western Bahia.

a federal (ANA) or a State agency). This database was consulted over an area of 24,000 hectares in Wester Bahia to calculate an average specific flow (l/s/ha) for irrigation. These authorizations reflect average climate conditions with an 80% precipitation guarantee level. The actual evapotranspiration estimate based on the methodology of the Brazilian Consumption Water Use Manual (ANA, 2019) is based on a larger number of weather stations and considers the main crops planted in 2013. The ETr of all estimates was calculated using the Penman-Monteith equation.

Initially, it is observed that SSEBop model represents well the trends of irrigation need, but also points out that there is important heterogeneity in water depths applied by the central pivots. The standard deviation is relatively high (□ = 0.09 to 0.17 l / s / ha) compared to the monthly average (μ = 0.43 to 0.54 l / s / ha).

The values estimated by SSEBop are very close to the indirect estimate for 2013, with variations of around 5% in May, July and August; 11% in June; and 19% in September. The comparability of the results in September is impaired due to the interpolation process in this month, since images of the following month (October) were not used, and the last available values of September were adopted until the end of the month.

Regarding the grant, the differences over the SSEBop estimate range from 11% in September to about 27% in May, July and August, and 15% in June. Considering that the grants are given considering a maximum planting per area with high water guarantee, the values are consistent with each other keeping the same monthly trend of increase/decrease.

The monthly average values estimated by SSEBop reflect the tendency of intensification of water use in the driest period. On the other hand, the standard deviation of daily values in relation to the average is high in all months, being higher at the peak of the dry season. This trend, shown in

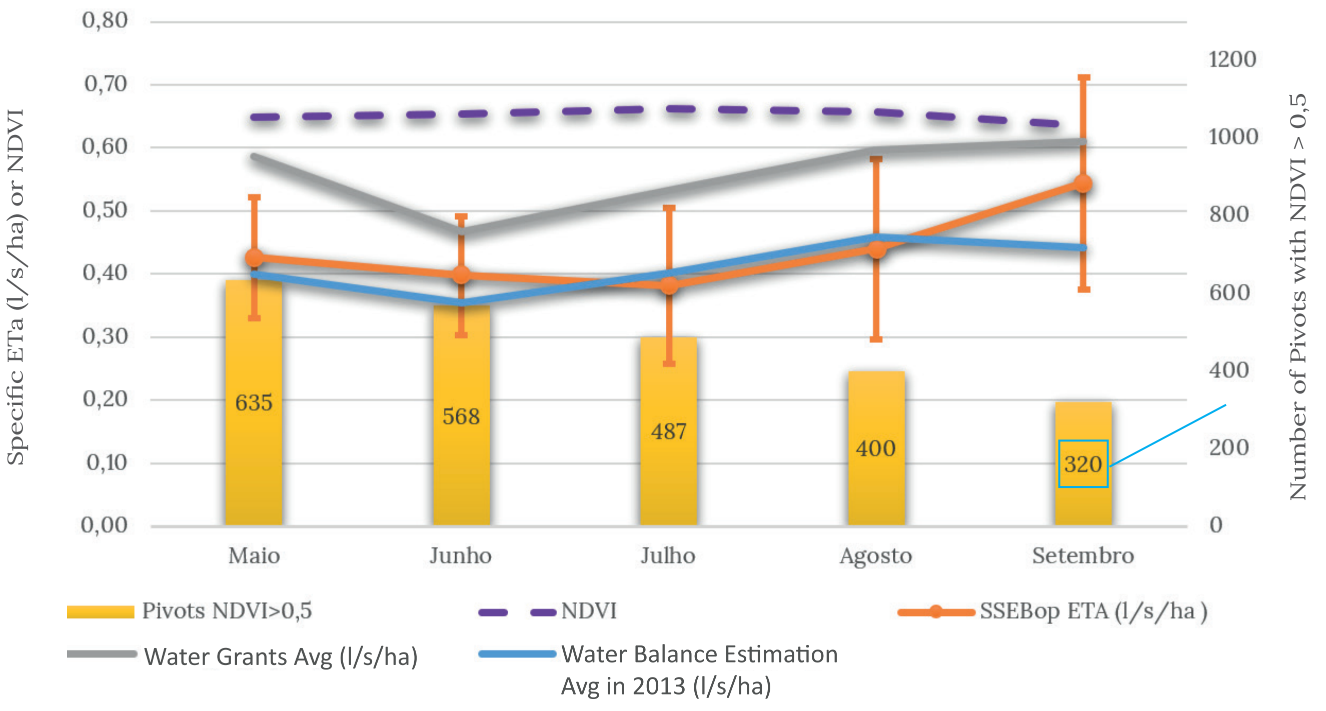


Figure 6. Evaluation of the ETa estimate by SSEBop in Western Bahia.

Figure 6, is compatible with field surveys in the region (ANA, 2005) that concluded that water management is inappropriate at several farms: few farmers apply the correct amount of water; and the majority applies less than necessary (68% of the sprinkler projects analyzed).

Regarding the total water consumption in the analyzed pivots, it is observed that although the irrigated area and the number of potentially active pivots decrease sharply as the dry season advances, the consumption decreases little due to the greater need for irrigation (following highest potential evapotranspiration trends). Between July and August, water consumption decreased by 10% while irrigated area decreased by 22%. Between August and September, consumption decreased by only 5% while irrigated area decreased by 24%.

As an additional analysis, Figure 7 presents a synthesis with the trends of ETa values for the 322 pivots that had NDVI ≥ 0.5 in September. ETa and NDVI trends are consistent, and the dispersion of NDVI values is greater over the first three months, which do not happen in August and September, when the highest ETa values occur.

The application of the SSEBop model in western Bahia demonstrates the ability to represents the spatiotemporal variability of actual evapotranspiration. The analyzes were deepened in central pivot irrigation areas and the model was able to portray the main trends of irrigation water consumption, in line with other indirect reference estimates. The model also portrayed the great variability in water use management between pivots, with high standard deviations, which is compatible with the highly variable management in the region and the different stages of crop development at the time that satellite passes.
In short, SSEBop estimates were consistent when compared with other indirect sources, which allows us to verify the adherence of values with locally expected values.

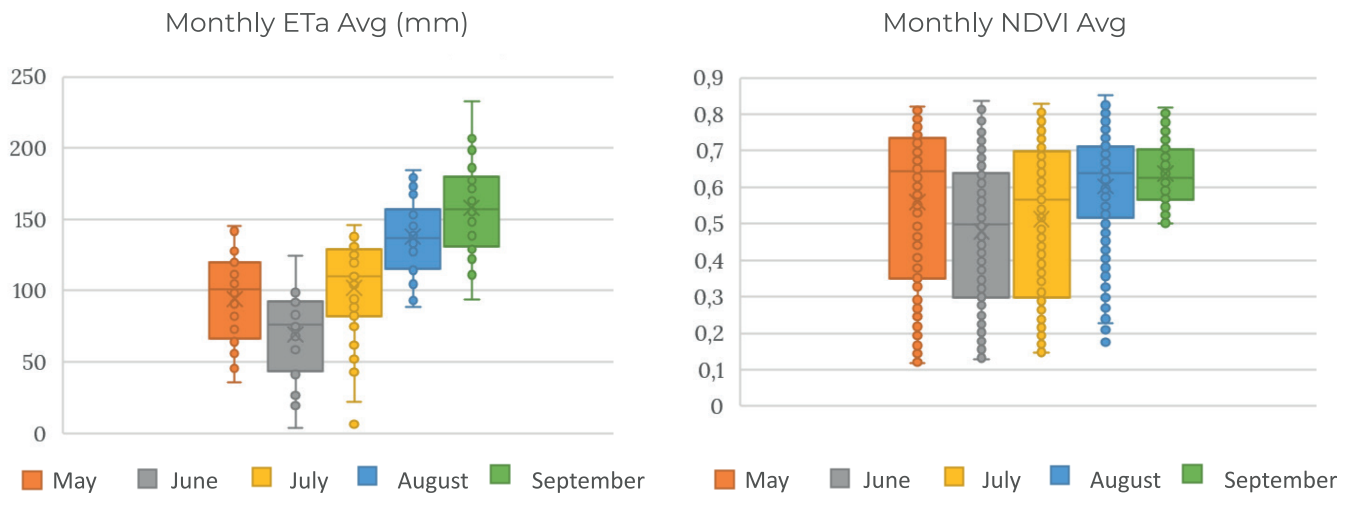


Figure 7. Comparison of ETa (mm) and NDVI tredns in the 322 pivots with NDVI ≥ 0.5 in September (Western Bahia).

Another analysis was conducted using field data - 37 daily Eta observations were obtained through Bowen Ratio (RB) and 85 other observations measured by flux towers (Eddy Covariance), a total of 122 daily observations. Observations were conducted in seven locations in three Brazilian states (Goiás and Distrito Federal in the central region of Brazil; and Rio Grande do Sul in the South). Data covers five different crops - soybeans, beans, wheat, rice and carrots (Diaz et al., 2019; Lopes et al., 2019; Paula et al., 2019; Souza et al., 2019).

It should be noted that field ETa estimation is not trivial, with some degree of uncertainty persisting as a function of the sensors applied, data processing, calculation routines and environmental and operating conditions.

Figure 8 presents comparative graphs of the actual evapotranspiration results estimated by SSEBop BR with estimated field data. Figure 8 also presents additional information about the analyzed locality, the estimation method and results. Although all graphs refer to SSEBop BR results using INMET's (Brazilian Meteorological Institute) network of stations (consolidated by Xavier et al., 2013), statistics are also presented using the GLDAS and CFSv2 meteorological data sources.

In all results the coefficient of determination R^2 is expressed, which indicates in percentage how much the model can explain observed values. Values closer to 1 (= 100%) means that the model fits very well the observed data.

In all cultures analyzed at least one, and most of the time, two of the meteorological data sources obtained R^2 above 0.7, and R^2 values above 0.8 were frequent. In some cases, the global models GLDAS and/or CFSv2 presented higher determination coefficients in relation to the consolidated data from INMET's network.

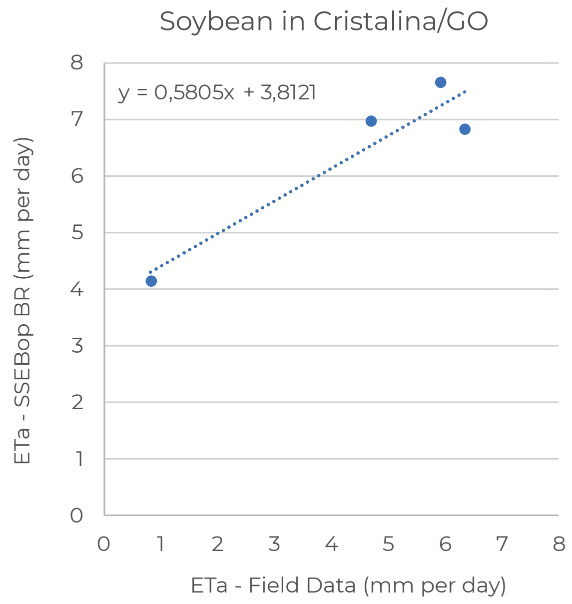
In the case of temporary crops in the Cerrado (Figure 8 - a, b, c, d and g), a vast tropical savannah biome, the SSEBop BR model can represent well the actual evapotranspiration behavior along time. With weather data from INMET stations, R^2 values ranged from 0.74 (Figure 8c) to 0.88 (Figure 8a). With CFSv2, R^2 higher than 0.95 and 0.94 were obtained in (a) and (g), respectively (Figure 8).

In the two cases where there is a greater volume of data in the same region, such as the flux towers in rice fields in the South (Figure 8e and 8f), the coefficient of determination ranged from 0.58 to 0.8, varying according to meteorological data sources. In the flux tower located in Cachoeira do Sul/RS, a R^2 of 0.72 (with CFSv2) was obtained; and in the tower in Paraíso do Sul/RS the R^2 was 0.8. Thus, a good model performance is inferred when compared to extensive and consistent series of field data also in flooded rice fields, although evapotranspiration models may present limitations in the period of water exposure when the crop has not yet emerged (no biomass).

(a)

Coordinates	-16,1937; -47.47335
Municipality/State	Cristalina/GO
Crop type	Soybean
Date	Nov/2014 to Feb/2015
Observations	4
ETa field method	Bowen Ratio
BR-MetData	R^2 0,88
GLDAS	R^2 0,92
CFSv2	R^2 0,95

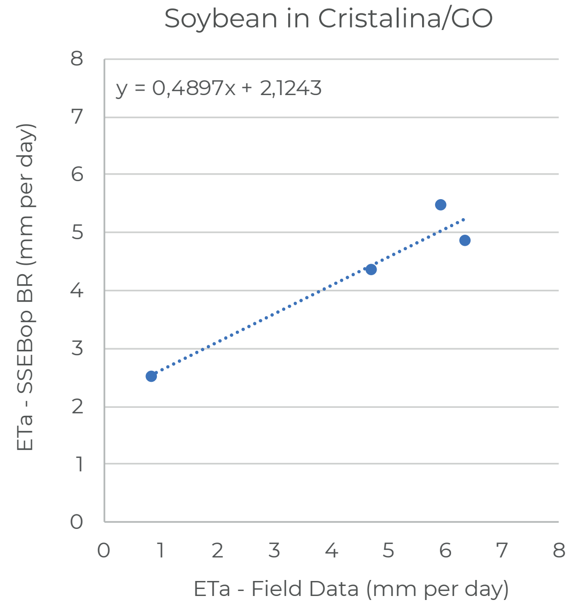
Note: comparison chart with BR-MetaData



(b)

Coordinates	-16.2049; 47.4587
Municipality/State	Cristalina/GO
Crop type	Soybean
Date	Jan/2015 to Feb/2015
Observations	4
ETa field method	Bowen Ratio
BR-MetData	R^2 0,84
GLDAS	R^2 0,85
CFSv2	R^2 0,78

Note: comparison chart with BR-MetaData



(c)

Coordinates	-15.909910°; -47.419410°
Municipality/State	Distrito Federal / DF
Crop type	Bean
Date	May/2015 to Aug/2015
Observations	8
ETa field method	Bowen Ratio
BR-MetData	R^2 0,74
GLDAS	R^2 0,52
CFSv2	R^2 0,37

Note: comparison chart with BR-MetaData

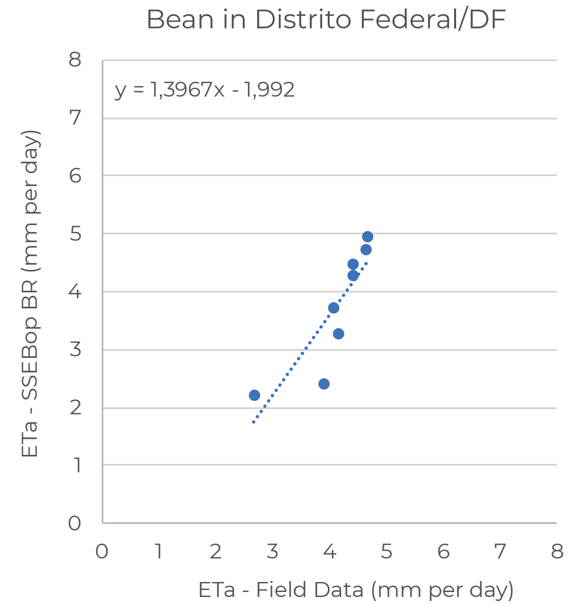
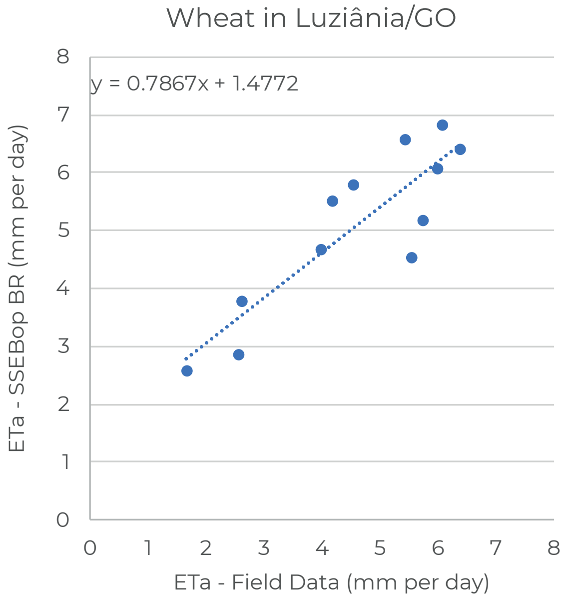


Figure 8 (a), (b) e (c). Comparison of SSEBop BR model results with field data.

(d)

Coordinates	-16.252260°;-47.683750°
Municipality/State	Luziânia/GO
Crop type	Wheat
Date	June/2017 to Sept/2017
Observations	12
ETa field method	Bowen Ratio
BR-MetData	R^2 0,77
GLDAS	R^2 0,81
CFSv2	R^2 0,73

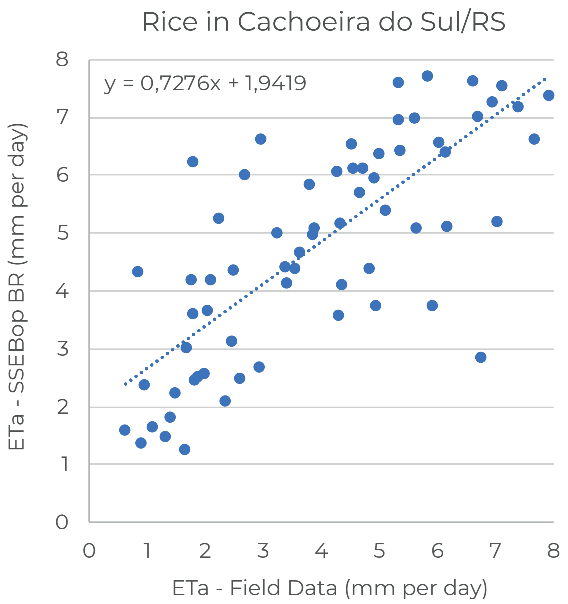
Note: comparison chart with BR-MetaData



(e)

Coordinates	-30.277082°; -53.14847°
Municipality/State	Cachoeira do Sul /RS
Crop type	Rice
Date	Dec/2010 to March/2015
Observations	68
ETa field method	Eddy Covariance
BR-MetData	R^2 0,58
GLDAS	R^2 0,65
CFSv2	R^2 0,72

Note: comparison chart with BR-MetaData



(f)

Coordinates	-29.744333°;-53.149944°
Municipality/State	Paraíso Sul /RS
Crop type	Rice
Date	Aug/2003 to July/2004
Observations	17
ETa field method	Eddy Covariance
BR-MetData	R^2 0,8
GLDAS	R^2 0,63
CFSv2	R^2 0,77

Note: comparison chart with BR-MetaData

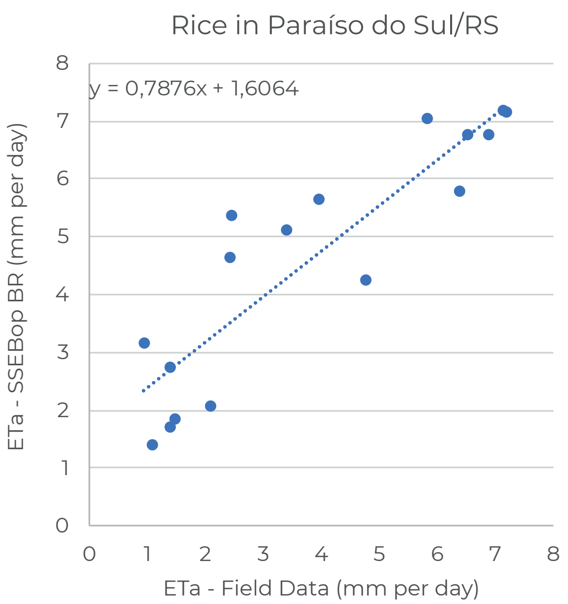


Figure 8 (d), (e) e (f). Comparison of SSEBop BR model results with field data.

(g)

Coordinates	-16.163830°;-47.481830°
Municipality/State	Cristalina/GO
Crop type	Carrot
Date	July/2014 to Oct/2014
Observations	9
ETa field method	Bowen Ratio
BR-MetData	R^2 0,86
GLDAS	R^2 0,7
CFSv2	R^2 0,94

Note: comparison chart with BR-MetaData

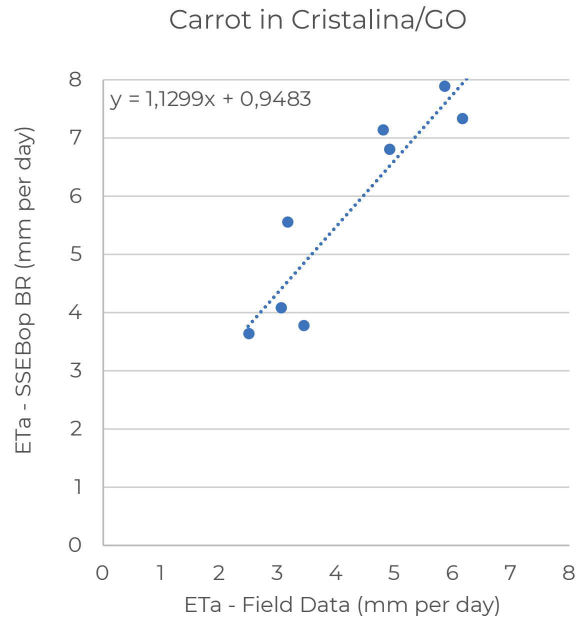


Figure 8 (g). Comparison of SSEBop BR model results with field data.

Note: in (d), BR-MetData represents the historical daily average from 2019/08/01.

Sources: SSEBop Estimate (y axis): SSEBop BR Application (http://bit.ly/ssebopbr).

Field data (x axis) and acknowledgments:
(a) Paula et al. (2019). Adriano Cesar Pereira de Paula (UnB) and Morris Scherer-Warren (ANA).
(b) Paula et al. (2019). Adriano Cesar Pereira de Paula (UnB) and Morris Scherer-Warren (ANA).
(c) Paula et al. (2019). Adriano Cesar Pereira de Paula (UnB) and Morris Scherer-Warren (ANA).
(d) Lopes et al. (2019). Juliana Dias Lopes (ANA).
(e) Diaz et al. (2019) and Souza et al. (2019). Débora Regina Roberti (UFSM) and staff from the UFSM Micrometeorology Laboratory.
(f) Souza et al. (2019). Débora Regina Roberti (UFSM) and staff from the UFSM Micrometeorology Laboratory.
(g) Data provided by Morris Scherer-Warren (ANA).

Other comparative evaluations were performed in São Marcos river basin, using field-measured and seasonally accumulated data. São Marcos river basin is located at Cerrado biome and it is the most intensive area of irrigation by center pivos in Brazil. Water withdrawals coordinates were associated with the respective irrigated areas in farms monitored by ANA. The volumes measured by hydrometers and hour meters were added to the rain incident on irrigated areas, estimated by the Climate Hazards Group Infrared Precipitation with Stations (CHIRPS/USGS) model (Funk et al., 2015). An efficiency of 85% was adopted to compare the data {Eta vs ((Measured Volume + Precipitation) * 0.85)}.

The SSEBop BR ETa was estimated for the Landsat 7 and 8 on the satellite's passing dates for pixels within the center pivots evaluated. For days without images or with clouds/shadows, simple linear interpolation was performed between days with images to obtain daily ETa, and then seasonally summed over the periods indicated for the respective study areas (indicated by colors in Figures 9 and 10).

Figure 9 presents the results for 9 water pumpings that supply 11 central pivots (a total of 1,095 ha), in three distinct periods (indicated by colors). The field data come from ANA inspection actions that consolidated and consisted monthly water withdrawals data sent by users and accompanied by photographic records of the respective water meters/hour meters.

The data estimated by SSEBop BR model showed good adherence with the monthly measured volumes added to the incident precipitation in all withdrawals - the determination coefficient R^2 was 94% (0.94) (Figure 9).

Municipality/State	Cistalina/GO, Paracatu/MG and Unai/MG
Crop type	Grains
Date	2018/2019
Observations	9 catchments / 11 pivots
Field data	Hydrometer or Hour Meter
BR-MetData	R^2 0,94

Season Period:

- May to August / 2018
- May to September / 2018
- October/2018 to January/2019

Sources:

SSEBop Estimate (y axis): SSEBop BR Application

Field data (x axis): Monthly water use statements from selected water users, accompanied by photographic records, and consisted by ANA.

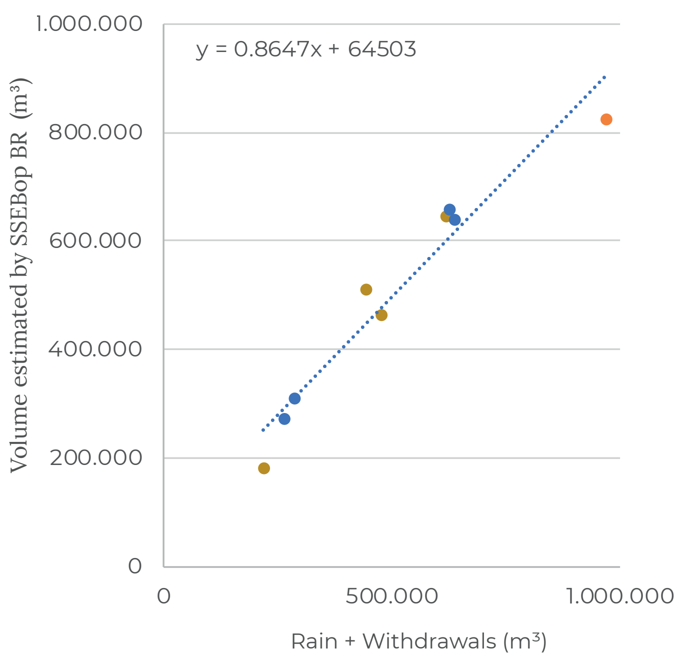


Figure 9. Comparison of SSEBop BR model results with measured field data from selected users.

Adopting the same procedure, Figure 10 presents the results for 13 water pumpings that supply 25 central pivots in a total of 2,015 hectares (Sado et al., 2018). The period analyzed was from July 2015 to May 2016.

The determination coefficient R^2 was 97% (0.97), with good adherence in all catchments when SSEBop BR performance is compared with measured field data.

These expeditious assessments expressed in the results of Figures 09 and 10 demonstrate that the SSEBop BR model also has potential for application in seasonal analyzes for water balance and for water regulation and inspection purposes. The larger the number of images and the smaller the influence of the incident precipitation on the ETa - more common situation in the dry season in the Cerrado biome, greater is model accuracy.

Municipality/State	Cistalina/GO and Paracatu/MG
Crop type	Bean and soybean
Date	July/2015 to May/2016
Observations	13 catchments / 25 pivots
Field data	Hydrometer
BR-MetData	R^2 0,97

Sources:

SSEBop Estimate (y axis): SSEBop BR Application

Field data (x axis): Sado et al. (2018).

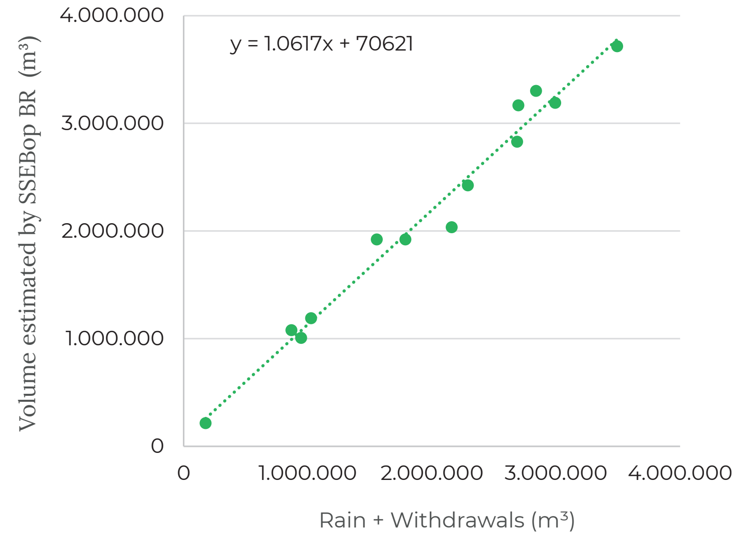


Figure 10. Comparison of SSEBop BR model results with measured field data from selected users.

Plantations close to the Pardo river on the border between Jaborandi and Morro Agudo municipalities (São Paulo State)
Raylton Alves / NA Image Bank

4 FINAL CONSIDERATIONS

Reservoir in the Paranapanema river basin
Raylton Alves / ANA Image Bank

Evapotranspiration estimates have several applications - hydrological modeling and irrigated agriculture are the main topics for water resources planning and regulation.

The SSEBop BR model relies on orbital remote sensing data to estimate actual evapotranspiration, so it has temporal limitations and is very sensitive to cloud cover. On the other hand, the analyzes conducted show that the model is able to represent the spatial and temporal variability of evapotranspiration with good precision. The accuracy and predictive power of the model increases as there are more cloud-free images, which should also occur with the launch of new orbital sensors capable of obtaining surface temperature.

The effort of parameterization and implementation of the SSEBop BR model for the Brazilian reality, carried out by ANA in partnership with the USGS, has shown excellent results when compared with field data and water balance estimates in irrigated areas. The availability of results throughout the national territory, from 1984 to present, through an easy-to-use online operational tool, fulfills the role of providing transparency and accessibility to general public.

As at any modeling processes, expanding SSEBop BR evaluations are desirable and necessary. This may result in suggestions for calibrations and parameterization, including regional ones. For this challenge, ANA will continue to develop the model and also count on collaboration of the scientific community and general users, who can share data and analysis aiming model improvements and its applications.

The development of tools such as SSEBop BR assists identification of special water management areas and on gathering more detailed information in these regions, especially regarding to water supply and demand. More detailed data support decision-making for the compatibility of multiple uses and water users risk management.

More information on Brazilian irrigated agriculture can be accessed in other ANA's publications (www.ana.gov.br) and in the National Water Resources Information System website (www.snirh.gov.br).

Irrigated plantation near Parnaíba (Piauí State)
Zig Koch / ANA Image Bank

REFERENCES

AGÊNCIA NACIONAL DE ÁGUAS (Brasil). **Atlas irrigação**: uso da água na agricultura irrigada. Brasília: ANA, 2017.

_______. **Manual de Usos Consuntivos da Água no Brasil**. Brasília: ANA, 2019.

ALLEN, R. G.; PEREIRA, L. S.; RAES, D. and SMITH, M. Crop evapotranspiration Guidelines for computing crop water requirements. **FAO Irrigation and drainage paper 56**. FAO, Rome, 1998.

ALLEN, R. G.; TASUMI, M. and TREZZA, R. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC)—Model. **Journal of Irrigation and Drainage Engineering**, v. 133, p. 380–394, 2007.

ALLEN, R. G.; PEREIRA, L. S.; Howell, T. A. and JENSEN, M. E. Evapotranspiration information reporting: I. Factors governing measurement accuracy. **Agricultural Water Management**, v. 98, n.6, p. 899–920, 2011.

DIAZ, M. B.; ROBERTI, D. R.; CARNEIRO, J. V.; SOUZA, V. de A. and MORAES, O. L. L. de. Dynamics of the superficial fluxes over a flooded rice paddy in southern Brazil. **Agricultural and Forest Meteorology**, p. 276-277, 2019.

FARR, T. G. and KOBRICK, M. Shuttle Radar Topography Mission produces a wealth of data. **Eos, Transactions American Geophysical Union**, n. 81, p. 583–585, 2000.

FUNK, C. PETERSON, P., LANDSFELD, M. et al. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. **Scientific Data**, v.2, 150066. DOI https://doi.org/10.1038/sdata.2015.66, 2015.

GLENN, E. P.; NEALE, C. M.; HUNSAKER, D. J. and NAGLER, P. L. Vegetation index-based crop coefficients to estimate evapotranspiration by remote sensing in agricultural and natural ecosystems. **Hydrological Processes**, v. 25, p. 4050–4062, 2011.

GOWDA, P.; CHAVEZ, J.; COLAIZZI, P.; EVETT, S.; HOWELL, T. and TOLK, J. Remote sensing-based energy balance algorithms for mapping ET: Current status and future challenges. **Transactions of the ASABE**, v. 50, p. 1639–1644, 2007.

IRMAK, A.; ALLEN, R. G.; KJAERSGAARD, J.; HUNTINGTON, J.; KAMBLE, B.; TREZZA, R. and RATCLIFFE, I. Operational Remote Sensing of ET and Challenges. **Evapotranspiration - Remote Sensing and Modeling**, DOI: 10.5772 / 25174, 2012.

IRONS, J. R.; DWYER, J. L. and BARSI, J. A. The next Landsat satellite: The Landsat data continuity mission. **Remote Sensing of Environment**, v. 122, p. 11-21, 2012.

KALMA, J. D.; MCVICAR, T. R. and MCCABE, M. F. Estimating land surface evaporation: A review of methods using remotely sensed surface temperature data. **Surveys in Geophysics**, v. 29, p. 421–469, 2008.

LI, Z.-L.; TANG, R.; WAN, Z.; BI, Y.; ZHOU, C.; TANG, B.; YAN, G. and ZHANG, X. A review of current methodologies for regional evapotranspiration estimation from remotely sensed data. **Sensors**, v. 9, no. 5, p. 3801–3853, 2009.

LOPES, D. J.; RODRIGUES, L. N.; IMBUZEIRO, H. M. A and PRUSKI, F. F. Performance of SSEBop model for estimating wheat actual evapotranspiration in the Brazilian Savannah region. **International Journal of Remote Sensing**, v. 40, p. 6930-6947, 2019.

McSHANE, R. R.; DRISCOLL, K. P. and SANDO, R. **A review of surface energy balance models for estimating actual evapotranspiration with remote sensing at high spatiotemporal resolution over large extents**. U.S. Geological Survey Scientific Investigations Report, n. 5087, 2017.

MORIASI, D. N.; ARNOLD, J. G.; VAN LIEW, M. W.; BINGNER, R. L.; HARMEL, R. D. and VEITH, T. L. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. **Transactions of the ASABE**, v. 50 (3): p. 885–900, 2007.

MECIKALSKI, J. R.; DIAK, G. R.; ANDERSON, M. C. and NORMAN, J. M. Estimating fluxes on continental scales using remotely sensed data in an Atmospheric–Land Exchange Model. **Journal of Applied Meteorology**, v. 38, no. 9, p. 1352–1369, 1999.

NORMAN, J. M.; KUSTAS, W. P. and HUMES, K. S. Source approach for estimating soil and vegetation energy fluxes in observations of directional radiometric surface temperature. **Agricultural and Forest Meteorology**, v. 77, no. 3–4, p. 263–293, 1995.

PAULA, A. C. P. de; SILVA, C. L. da; RODRIGUES, L N. and SCHERERWARREN, M. Performance of the SSEBop model in the estimation of the actual evapotranspiration of soybean and bean crops. **Pesquisa Agropecuária Brasileira**, v. 54, e00739, 2019.

RITTER, A. and MUÑOZ-CARPENA, R. Performance evaluation of hydrological models: statistical significance for reducing subjectivity in goodness-of-fit assessments. **Journal of Hydrology**, v. 480 (1), p.33–45, 2013.

RODELL, M. et al. The Global Land Data Assimilation System. **Bull. Amer. Meteor. Soc.**, v. 85(3), p. 381-394, 2004.

SADLER, E. J.; BAUER, P. J.; BUSSCHER, W.J. and MILLEN, J.A. Site-specific analysis of a droughted corn crop: water use and stress. **Agronomy Jornal**, v. 92, p. 403-410, 2000.

SADO, R. R.; WARREN, M. S.; and ROIG, H. L. Estimativa de irrigação por meio de sensoriamento remoto na bacia hidrográfica do Alto São Marcos. **Rev. Bras. de Cartografia**, vol. 70, n. 3, p. 787-802, 2018.

SAHA, S., et al. **NCEP Climate Forecast System Version 2 (CFSv2) 6-hourly Products**. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory, 2011. Disponível em: <https://doi.org/10.5065/D61C1TXF>. Acesso: 03 maio 2019.

SANTOS, C.; LORITE, I. J.; TASUMI, M., ALLEN, R.G. and FERERES, E. Integrating satellite-based evapotranspiration with simulation models for irrigation management at the scheme level: **Irrigation Science**, v. 26, n. 3, p. 277–288, 2008.

SAVOCA, M.E.; SENAY, G.B.; MAUPIN, M.A.; KENNY, J.F. and PERRY, C.A. **Actual evapotranspiration modeling using the operational Simplified Surface Energy Balance (SSEBop) approach**. U.S. Geological Survey Scientific Investigations Report, n. 5126, 2013.

SENAY, G. B.; BUDDE, M.; VERDIN, J. P. and MELESSE, A. M. A coupled remote sensing and simplified surface energy balance approach to estimate actual evapotranspiration from irrigated fields. **Sensors**, v.7, p. 979–1000, 2007.

SENAY, G. B.; BOHMS, S.; SINGH, R. K.; GOWDA, P. H.; VELPURI, N. M.; ALEMU, H. and VERDIN, J. P. Operational evapotranspiration mapping using remote sensing and weather datasets: A new parameterization for the SSEB approach. **JAWRA Journal of the American Water Resources Association**, v. 49, n. 3, p. 577-591, 2013.

SOUZA, V. A.; ROBERTI, D. R.; RUHOFF, A. L.; ZIMMER, T.; ADAMATTI, D. S.; GONÇALVES, L. G. G.; DIAZ, M. B.; ALVES, R. C. M. and MORAES, O. L. L. Evaluation of MOD16 algorithm over irrigated rice paddy using flux tower measurements in Southern Brazil. **Water**, v. 11, 1911, 2019.

SENAY, G.B.; FRIEDRICHS, M.; SINGH, R.K. and VELPURI, N.M. Evaluating Landsat 8 evapotranspiration for water use mapping in the Colorado River Basin. **Remote Sens. Environ**, v. 185: p.171–185, 2016.

SENAY, G. B.; SCHAUER, M.; FRIEDRICHS, M.; VELPURI, N. M. and SINGH, R. K. Satellite-based water use dynamics using historical Landsat data (1984–2014) in the southwestern United States. **Remote Sensing of Environment**, v. 202, p. 98-112, 2017.

SENAY, G. B. Satellite Psychrometric Formulation of the Operational Simplified Surface Energy Balance (SSEBop) Model for Quantifying and Mapping Evapotranspiration. **Applied Engineering in Agriculture**, v. 34, n. 3, p. 555-566, 2018.

SU, Z. The Surface Energy Balance System (SEBS) for estimation of turbulent heat fluxes. **Hydrology and Earth System Sciences**, v. 6, no. 1, p. 85–100, 2002.

TASUMI, M. et al. At-surface reflectance and albedo from satellite for operational calculation of land surface energy balance. **Journal of hydrologic engineering**, v. 13, n. 2, p. 51-63, 2008.

WALTER, I. A. et al. ASCE's standardized reference evapotranspiration equation. **Watershed management and operations management 2000**, p. 1-11, 2000.

XAVIER, A. C.; KING, C. W. and SCANLON, B. R. Daily gridded meteorological variables in Brazil (1980–2013). **International Journal of Climatology**, v. 36, p. 2644–2659, 2016.

ANA
NATIONAL WATER AGENCY - BRAZIL

MINISTRY OF
REGIONAL DEVELOPMENT

PÁTRIA AMADA
BRASIL
BRAZILIAN GOVERNMENT