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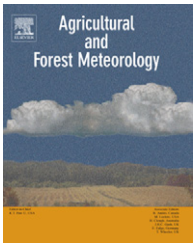

Reviewing SEBAL input parameters for assessing evapotranspiration and water productivity for the Low-Middle São Francisco River basin, Brazil

Part A: Calibration and validation

A.H. de C. Teixeira [a,*], *W.G.M. Bastiaanssen* [b,c], *M.D. Ahmad* [d,e], *M.G. Bos* [f]

[a] *Embrapa Semi-Árido, P.O. Box 23, 56302-970 Petrolina, PE, Brazil*
[b] *WaterWatch, Generaal Foulkesweg 28, 6703 BS, Wageningen, The Netherlands*
[c] *Delft University of Technology, Stevinweg 1, 2600 GA, Delft, The Netherlands*
[d] *Formerly with International Water Management Institute, P.O. Box 2075, Colombo, Sri Lanka*
[e] *Currently at CSIRO Land and Water, GPO Box 1966, Canberra act 2601, Australia*
[f] *Formerly with International Institute for Geo-Information Science and Earth Observations, P.O. Box 6, 7500 AA, Enschede, The Netherlands*

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ABSTRACT

There is a growing interest in quantifying regional scale actual evapotranspiration (ET) for water accounting and for water productivity assessments at river basin scale. Methods that provide point values fail to describe the situations at larger scales. Remote sensing measurements can be used at different spatial scales. This paper applies the theory of the Surface Energy Balance Algorithm for Land (SEBAL). SEBAL was originally derived for Egypt, Spain and Niger [Bastiaanssen, W.G.M., 1995. Regionalization of surface flux densities and moisture indicators in composite terrain: a remote sensing approach under clear skies in Mediterranean climates. Ph.D. dissertation, CIP Data Koninklijke Bibliotheek, Den Haag, The Netherlands. 273 pp.] and was calibrated and validated using ground measurements from four flux sites and from seven agro-meteorological stations in the semi-arid region of the Low-Middle São Francisco River basin, Brazil. Measured parameters included surface albedo, surface temperature, atmospheric and surface emissivity, soil heat flux, surface roughness, net radiation, air temperature gradients, sensible heat flux, latent heat flux, evaporative fraction, and photosynthetically active radiation. The daily ET was estimated (RMSE of 0.38 mm d^{-1}) for mixed agricultural and natural ecosystems. The improved coefficients for the local conditions can now be used to study the impact of expanding irrigated agriculture on the regional water balance and to quantify the water productivity of irrigated horticulture that is the largest water consumer in the Brazilian semi-arid region. Both applications are described in an accompanying paper (Part B).

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[*] *Corresponding author*. Tel.: +55 87 38621711; fax: +55 87 38621744.
E-mail address: heribert@cpatsa.embrapa.br (A.H. de C. Teixeira).

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1. Introduction

Irrigated agriculture in the semi-arid region of the São Francisco River basin (North-east Brazil) constitutes an important activity for livelihood of rural communities. The potential for fruit production in this region has been confirmed by the continuous expansion of irrigated land. Vineyards and mango orchards are the major crops. These land use changes affect the regional scale water balance.

Together with rainfall and runoff, the ET controls the availability of water at the Earth's surface (McCabe and Wood, 2006). The accurate determination of ET significantly reduces uncertainties in the water balance of a (sub-)basin (Cleugh et al., 2007), providing water managers with information on (i) water resources being consumed and thus not longer available for downstream users, and (ii) water productivity, i.e. the consumption of water in terms of biomass production per unit of water (e.g. Steduto et al., 2007).

Field scale ET measurements on vineyards, mango orchard and natural vegetation (caatinga) were done in the Low-Middle São Francisco River basin. Micro-meteorological methods were used providing point values for specific sites (Teixeira et al., 2007, 2008a,b). Direct extrapolations of data from individual flux sites to the regional scale can lead to biased estimates, because a few flux sites cannot provide a fair sample of a larger area (Wylie et al., 2003).

According to Nagler et al. (2005), species-level vegetation maps and species-specific algorithms would be needed for scaling tower-based ET data to larger areas. Species maps are difficult to construct even with high-resolution aerial photography. Pelgrum and Bastiaanssen (1996) confirmed this difficult with the use of field data from 13 flux towers in a heterogeneous landscape in central Spain with irrigated crops, rainfed crops and natural vegetation being insufficient, because the spatial variations of these latent heat fluxes are dictated by plant spacing, leaf area index, soil wetness, etc. Therefore, data from flux stations are only a first estimate of ET from contrasting ecosystems (Leuning et al., 2005).

Allen et al. (2007b) summarized a number of examples of remote sensing applications for irrigation management issues in the Western U.S. Bastiaanssen and Harshadeep (2005) reported a range of applications in Asia. The major advantage of remote sensing is that the ET at a large scale can be computed on pixel-to-pixels basis applying a consistent set of equations that utilize unique spectral radiances for each pixel.

The spatial and temporal distribution of ET can be mapped from remote sensing techniques without going through excessive ground truth data collection (e.g. Franks and Beven, 1999). According to Nagler et al. (2007), remotely sensed vegetation indices, obtained as a time series over a growing season, and micrometeorological data can be used to extrapolate plot level measurements of ET and water productivity over larger landscapes units. Another advantage of remote sensing is that ET is sampled over many fields growing the same crop or over natural bush land. In this way it is possible to determine true averages for a certain ecosystem or region (Tasumi and Allen, 2007).

Jackson et al. (1977) pioneered in Arizona with the determination of ET by thermal remote sensing data, using infrared thermometry in wheat. Choudhury (1989), Schmugge and Becker (1991), Kustas and Norman (1996), Bastiaansssen et al. (1998a), Bastiaanssen et al. (1999), Kustas et al. (2004), Courault et al., 2005 and Allen et al. (2007a) provided reviews of the progressive development of remote sensing algorithms for the estimation of ET during the last 20 years.

These reviews basically concluded that after these years of research, algorithms are sufficiently robust to be used for water management. One of these algorithms is the Surface Energy Balance Algorithm for Land (SEBAL). SEBAL has been applied to a variety of ecosystems (Bastiaansssen et al., 1998b; Bastiaanssen et al., 1999; Bastiaansssen et al., 2001; Bastiaanssen et al., 2002, 2005, 2008; Wang et al., 1998; Bastiaansssen, 2000; Farah and Bastiaanssen, 2001; Bastiaanssen and Bandara, 2001; Ahmad and Bastiaanssen, 2003; Bastianssen and Chandrapala, 2003; Chemin et al., 2004; Allen et al., 2005; El-Magd and Tanton, 2005; Akbari et al., 2007; Immerzeel et al., 2008).

SEBAL was introduced in the São Francisco River basin in 2000 (Bastiaansssen et al., 2001). This introduction has prompted Embrapa (Brazilian Agricultural Research Corporation) to use remote sensing for the up scaling of local water fluxes and water productivity in the basin. Although this algorithm was designed to calculate the energy balance at regional scale using a minimum of ground data, local parameterization of any remote sensing equations can improve the accuracy of the model (Duchemin et al., 2006).

This paper combined satellite data, field measurements of the surface radiation and energy balances and agro-meteorological stations to review the various SEBAL steps. During this process, the accuracy of individual empirical relationships, as well as the final validation of daily regional evapotranspiration, was investigated. The reviewed parameters were; surface albedo, surface temperature, surface and atmospheric emissivities, roughness length for momentum transport, net radiation, soil heat flux, air temperature gradient, sensible heat flux, latent heat flux, and photosynthetically active radiation. The relevant equations were adapted for the semi-arid conditions in the Low-Middle São Francisco River basin, and then applied to each individual Landsat image.

2. Material and methods

2.1. *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 energy balance equation. This is accomplished by first computing the regional surface radiation balance, followed by the regional surface energy balance. The schematic overview to convert spectral radiances into the net radiation using Landsat images is presented in Fig. 1.

The net shortwave radiation available at the earth surface depends on the incoming solar radiation (R_G) and the surface albedo (α_0). The second parameter is calculated from satellite-measured spectral radiances for each narrow band, followed by mathematical expressions for spectral integration and