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Models for assessment of actual evapotranspiration from remote sensing: Theoretical basis

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Abstract. In the evaluation of the onset, severity and duration of situations of water stress and droughts, indicators based on processes with intensive use of remote sensing can be used. In the monitoring of agricultural activities as well as the management of water and forest resources, spatio-temporal distributions of information of actual evapotranspiration (ET_{act}) are crucial. This work presents the theoretical aspects of spatio-temporal assessment of ET_{act} process, from remote sensing and meteorological data.

Keywords. Remote sensing – GIS – Actual evapotranspiration – Land surface temperature – NDVI.

Modèles pour l'évaluation de l'évapotranspiration réelle à partir de la télédétection : bases théoriques

Résumé. *L'apparition, la sévérité et la durée du stress hydrique et de la sécheresse, peuvent être évalués au moyen d'indicateurs basés sur les données de télédétection. Pour le suivi de la productivité agricole et pour la gestion des ressources hydriques, la distribution spatio-temporelle de l'évapotranspiration réelle,* ET_{act}, *est d'une grande importance. Cet article présente les aspects théoriques de l'évaluation spatio-temporelle de* ET_{act}, *à partir de la télédétection et des données météorologiques.*

Mots-clés. *Télédétection – GIS – Evapotranspiration réelle – Temperature de la superficie terrestre – NDVI.*

I – Introduction

The monitoring and modelling of land surface and vegetation processes is an essential tool for the assessment of water and carbon dynamics of terrestrial ecosystems (Verstraeten *et al.*, 2008). Several studies present the state of the art in the field of estimation of actual evapotranspiration (ET_{act}) from remote sensing (Couralt *et al.*, 2005; Olioso *et al.*, 2005; García *et al.*, 2006; Carlson, 2007). The spatial pattern of daily ET_{act} is important not only for the estimation of crop water requirements and water consumption, the analysis of climate processes, weather forecasting, the study of soil salinisation, and assessing aquifer recharge (SIRRIMED D4.3, 2011), but also for studies of the hydrological cycle at basin scale.

The spatio-temporal assessment of ET_{act} depends on the water status and the energy processes. These processes, in turn, are dependent on land use, distribution of rainfall and irrigation supply, soil properties and climatic factors. There is a need for development of an operational monitoring of ET_{act}.

A brief introduction of models for the estimation of ET_{act} are presented. These are based on balance of surface energy, surface temperature, derivations of the residual model, the relationship between vegetation indexes and land surface temperature (LST), and indirect methods (SVAT).

II – Classification of methodologies for estimation of ET_{act}

1. Models based on surface energy balance

The energy balance equation, without advection, is expressed as:

$$R_N = \lambda ET + H + G + PH \quad (1)$$

where R_N is the net radiation, λET is the latent heat flux or ET_{act} (λ latent heat of vaporization and ET flux of evaporated water), H is the sensible heat flux, G is the soil heat flux, and PH the energy used in the photosynthesis process. The magnitude order of PH is generally small, it is therefore negligible. The residual equation is usually used for the estimation of λET considering the following equation (Choudhury, 1994),

$$\lambda ET = R_N - G - H \quad (2)$$

However, when ET-retrieval methods from remote sensing are used, several uncertainties arise in the parameterization of the energy term (R_N – G), and especially of the term G, which can reach high values in arid and semiarid countries (SIRRIMED D4.3, 2011).

2. Models based on land surface temperature: derivations of the residual method

The surfaces where evapotranspiration occurs present a reduction in the temperature with respect to the non-evaporative surfaces. The level at which you set the surface temperature is an indicator of the distribution of the surface energy available for processes such as the flow of sensible and latent heat to the atmosphere, sensible heat flux to the ground and radiation into the atmosphere. The LST is a piece of readily-available remote sensing data. So, another expression derived from the residual equation, and known as "simplified equation", was considered for the assessment of ET_{act} (Jackson *et al.*, 1977; Delegido *et al.*, 1993),

$$ET_d = R_{Nd}^{*} - B \cdot (LST - T_a)_i \quad (3)$$

where ET_d is the daily actual evapotranspiration and R_{Nd}^{*} is the daily net radiation (both in mm/day), B is an empirical constant, and $(LST - T_a)_i$ is the difference between land surface and air temperature, both measured around noon.

For the determination of the constant B, measures of: evapotranspiration (lysimeter, method of "eddy-correlation", method of Bowen), daily net radiation, daily mean air temperature and LST (which is obtained through remote sensing) are all needed. With these data, the constant B is calculated from the regression line (ET_d - R_{Nd}^{*}) as a function of $(LST - T_a)_i$. Once B is obtained, it is possible to use the simplified equation for estimating evapotranspiration from LST, T_a and R_{Nd} data.

Later, this equation was improved by introducing a second parameter, A (Seguin, 1993):

$$ET_d = R_{Nd}^{*} + A - B\ (LST - T_a)_i \quad (4)$$

Net radiation data are difficult to obtain from conventional weather stations, which could therefore be a drawback for the simplified method. But, nowadays, estimation of net radiation could be obtained considering remote sensing data. However, the equation was modified to obtain an expression depending on global radiation (which is easier to get). The ET_0 is obtained with the following equation (Caselles *et al.*, 1992),

$$ET_0 = A\ .\ T_a^{máx}\ .\ R_g + B\ .\ R_g + C \quad (5)$$

where ET_0 is the reference crop evapotranspiration, $T_a^{máx}$ is the maximum air temperature, R_g daily global radiation, and *A*, *B* and *C* are empirical coefficients. There are several methods for estimating $T_a^{máx}$ and R_g from information obtained by remote sensing (Dedieu *et al.*, 1987).

3. Models based on the relationship between vegetation indexes and land surface temperature

A negative linear relationship between LST and vegetation indices (such as NDVI Normalized Vegetation Index), is generally observed. The LST decreases as the density of vegetation increases, which is explained by the cooling caused by ET_{act} (Caselles *et al.*, 1998). The slope of this linear relationship varies depending on the soil water availability, which depends on water balance (rainfall and evaporation).

There are several water stress indices based on remote sensing of LST, associating the ET_{act} with potential ET (ET_{pot}) to assess water requirements.

One of the first that was developed is the **CWSI** (Crop Water Stress Index), expressed as (Jackson *et al.*, 1981),

$$\frac{ET_{act}}{ET_{pot}} = \frac{LST - LST_{\max}}{LST_{\min} - LST_{\max}} = 1 - CWSI \qquad (6)$$

where ET_{act} is the actual evapotranspiration, ET_{pot} is the potential evapotranspiration, LST_{max} is the maximum *LST* in the study area, and LST_{min} is the minimum *LST* in the study area (Jackson *et al.*, 1981). This index is reliable only for surfaces with full cover of vegetation.

For composite surfaces (only partially covered by vegetation), a graphical method of *VITT trapezoid* (Vegetation Index/Temperature Trapezoid), presented in Fig. 1, is used. With this method it is possible to estimate the *WDI index* (Water Deficit Index, Moran *et al.*, 1994).

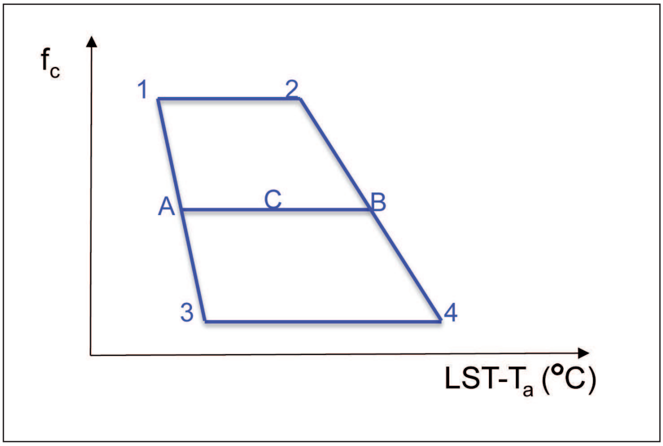

Fig. 1. VITT trapezoid (Vegetation Index-Temperature Trapezoid). Example for MODIS data, for Jucar River basin.

4. Indirect methods. SVAT Model

These methods are based in Soil-Vegetation-Atmospheric Transfer (Soil-Vegetation-Atmosphere Transfer, SVAT) models. The SVAT models require data from different wavelengths (while the methods mentioned thus far require mainly data in the thermal infrared or IRR), to calculate land surface characteristics such as albedo, emissivity and leaf area index (LAI) (Courault *et al.*, 2003).

Although SVAT models are designed to be coupled with atmospheric models, they can also be used to study the processes of evapotranspiration in an "off-line" mode (Bastiaanssen *et al.*, 2005). These models are suitable for ET evaluation in precision irrigation for short periods of time (hours), but have the disadvantage of requiring more initial data.

III – Algorithms derived from the residual method

All the selected algorithms are derived from the *residual method*. Once all the terms of surface energy balance equation have been estimated, ET_{act} is evaluated as the residual of the equation. The methodologies considered could be classified into two groups:

(i) Methods with direct estimation of sensible heat flux (Hs), estimating ET as the residual term of the surface energy balance equation:

– SM method (Simplified method),

– SEBAL model (Surface Energy Balance Algorithm for Land), and

– TSEB (Two Source Energy Balance model).

These are a direct application of the residual method, where:

$$\lambda ET = R_N - H_s - G \quad (7)$$

(ii) Methods with direct estimation of evaporative fraction (EF), and therefore ET_{act} (without estimation of H_s):

– Simplified SEBI method, S-SEBI (Soil Energy Balance Index), and

– JIC method (proposed by Jiang and Islam, 2001).

Where:

$$\lambda ET = EF \cdot (R_N - G) \quad (8)$$

Three of these methods (S-SEBI, SEBAL and JIC) are based on the contrast between the pixels of the wet zone and the dry zone. These methods require a prior graphical representation and interpretation of the data, therefore they are also named *graphical methods*. The net radiation R_N, at daily scale, as well as the flux of soil heat G, are needed for ET_{act} estimation.

1. The simplified method

In the simplified method, proposed by Carlson *et al.* (1995), the net daily evapotranspiration integrated in the surface ET_d, is estimated from a few data: *LST* near noon, when the satellite passes ($T_{s,i}$), air temperature ($T_{a,i}$), and net radiation expressed as the integrated value over 24 hours ($R_{n,d}$), as follows

$$R_{n,d} - \lambda ET_d = B \cdot (T_{s,i} - T_{a,i})^n \quad (9)$$

where B and n are parameters to be defined. $R_{n,d}$ and λET are expressed in cm day^{-1}. The term on the right of equation (9), represents an approximation of the daily sensible heat flux $H_{s,d}$, assuming that the soil heat flux is negligible at daily scale ($G_d \approx 0$). The term B could be considered as a coefficient of sensible heat flux transference by convection and n is a correction factor to take the stability of the atmosphere into account. An *unstable* situation (during the day, when the warmer air is below the cooler air), tends to increase the sensible heat flux, while the reverse situation (*stable* atmosphere), tends to inhibit this flux. Carlson *et al.* proposed a relationship among the *B* and *n* parameters, the vegetation fraction F_v and the corrected NDVI N^*, using the results from a SVAT simulation.

This method requires the following data: (i) spectral radiances in the red and NIR (for NDVI estimation), and *LST*, from remote sensing; and (ii) air temperature at surface level.

The main advantage of the simplified method is its simplicity. The drawback is its lack of precision, since the *B* and *n* parameters depend not only on the vegetation cover, but also of roughness height, wind velocity, and water status of soil and vegetation.

2. The SEBAL method

The SEBAL method developed by Bastiaanssen *et al.* (1998) is a direct application of the residual method, combining an empirical and physical parameterization. The input data include local meteorological data (mainly wind velocity), and remote sensing data (radiances and *LST*). From these data, the net radiation (R_n), NDVI, albedo (α), roughness height (z_0) and soil heat flux (G), are estimated. The sensible heat flux is estimated by contrasting two sites (one site of wet soil or with vegetation without water stress, and another site of dry soil). ET_{act} is derived as the residual term of the surface energy balance.

3. The TSEB algorithm

So far, the models presented consider a single source of water vapour at the surface. They do not distinguish contributions of vegetation and soil in the surface fluxes. Therefore, the use or the water stress of vegetation cannot be separated. In the models with the approach known as "Two sources" (Norman *et al.*, 1995; Kustas *et al.,* 2003; Melesse *et al.,* 2005), the estimation of surface energy balance at the surface is divided into two parts: one is related with the vegetation, and the other with the soil.

This model can reach, in certain cases, high accuracy (up to 90%), but it is more complex than other approaches, and requires very accurate *LST* information.

4. The S-SEBI algorithm

The S-SEBI scheme, proposed by Roerink *et al.* (2000), defines two temperature thresholds for a given surface albedo value: a maximum temperature, which corresponds to completely dry areas and a minimum temperature corresponding to surfaces that evaporate freely. These temperatures define the variation range of *LST* over the whole image, and are used for defining the evaporative fraction (*EF*). In the SEBI (Surface Energy Balance Index) method, the evapotranspiration estimated from the evaporative fraction is defined as follows,

$$EF = \frac{\lambda ET}{R_N - G} = \frac{\lambda ET}{\lambda ET + H_S} \tag{10}$$

The S-SEBI method presents two main advantages:

(i) It is a self-sufficient method while satellite data is available, and needs no ground measurement data.

(ii) From a physical point of view, and comparing it with the methods that determine a single temperature for both dry and wet conditions, the S-SEBI method is more realistic because it determines the value of these temperatures as a function of albedo.

The data required for the application of this method are: spectral radiances in the visible, near infrared and thermal infrared.

5. The JIC algorithm

The method proposed by Jiang *et al.* (2004), or the JIC method, is based on the analysis of LST-NDVI space. This space (triangular or trapezoidal form), delimited by the distribution of pixels, has a linear relationship with the surface fluxes of energy.

Figure 2 below presents an example of *LST*-NDVI space obtained from remote sensing. This triangle defines the limits for the evaporative fraction (*EF*). The estimation of latent heat flux is restricted in this space, which is the key to this method. From this space, the EF is linearly related with LST for a certain NDVI.

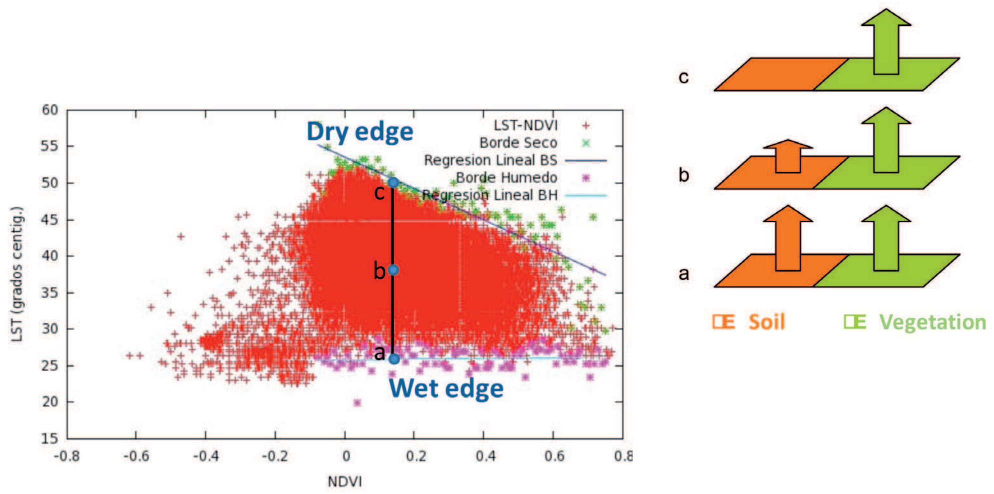

Fig. 2. Conceptual interpretation of LST *vs* NDVI (adapted from Jiang *et al.*, 2004). Example from MODIS data.

In this method, ET_{act} is based in the *Priestley-Taylor* equation and a relation between *LST* and NDVI (Jiang and Islam, 2001), is estimated as follows:

$$\lambda ET = \phi \frac{\Delta}{(\Delta + \gamma)}(R_N - G) \quad (11)$$

where Φ corresponds to *EF* value, Δ is the slope of the vapour pressure curve, γ the psychometric constant and R_N represents net radiation.

In conditions without convection and advection,

$$ET \leq (R_N - G) \tag{12}$$

Therefore, Φ presents the following range corresponding to minimum and maximum values of ET_{act}, respectively.

$$0 \leq \phi \leq \frac{\Delta}{(\Delta + \gamma)} \tag{13}$$

Each pixel of this LST-NDVI space has an associated specific Φ defined by:

$$\phi = \phi_{max} \frac{LST_{max} - LST}{LST_{max} - LST_{min}} \tag{14}$$

where Φ_{max} = 1.26 corresponds to bare soil, LST_{max} is the maximum LST for NDVI = 0, and LST_{min} the minimum LST. Then, a spatial distribution of Φ is obtained for each date.

The following equation represents the evaporative fraction (EF),

$$EF = \phi \frac{\Delta}{(\Delta + \gamma)} \tag{15}$$

where the psychometric constant is a function of atmospheric pressure.

The net radiation is estimated considering ground meteorological data, remote sensing data, and topographical attributes derived from a Digital Elevation Modelo (DEM), applying the following equation,

$$R_N = (1 - \alpha)\, R_s + R_L^{\downarrow} + R_L^{\uparrow} \tag{16}$$

where R_s is the solar radiation (or downward short wave radiation), $R_L^{\downarrow}$ and $R_L^{\uparrow}$ are downward and upward long wave radiation respectively. They were estimated considering the Stefan Law, with the clear sky emissivity calculated from an empirical relationship with e_a, and the surface emissivity.

IV – Conclusions

The monitoring of agricultural activities, land management, food security research, pollution detection, nutrient flows, fire detection, and carbon balance as well as hydrological modelling, require the estimation of evapotranspiration at different spatio-temporal resolutions. Several methods for the estimation of ET_{act}, considering an intensive use of remote sensing of earth systems, were presented. It is recommendable to validate the results of these methodologies with *in situ* data or ground truth.

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