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EVAPOTRANSPIRATION FROM A REMOTE SENSING MODEL FOR WATER MANAGEMENT IN AN IRRIGATION SYSTEM IN VENEZUELA

RICARDO TREZZA

SUMMARY

This paper explores the feasibility of the use of an energy balance model for the estimation of evapotranspiration from satellite data in a large irrigated area, the Río Guárico irrigation system, in Venezuela. A large water reservoir stores the water coming from the Guárico River and provides for irrigation of ~60,000ha. Rice is the main crop grown in the area. Despite water availability, the agricultural potential of the area has been limited by lack of appropriate water management and distribution. The satellite-based energy balance model used in this study was SEBAL (Surface Energy Balance Algorithm for Land), an image-processing model for calculating evapotranspiration (ET) as a residual of the surface energy balance, developed in the Netherlands, that has been applied in many developing countries. SEBAL uses satellite data collected by the LANDSAT Thematic Mapper (TM) or other satellite sensors collecting visible, near-infrared and thermal infrared radiation. The main advantage of SEBAL is the need of a minimum amount of ground data. The original model was modified and adapted for use with the specific conditions of the study area in Venezuela, using the FAO-56 methodology. The results suggest that SEBAL can be considered as an operational and feasible method to predict actual ET from irrigated lands having limited amount of ground information, which is a common situation in Venezuela.

The management of water resources is one of the biggest challenges for mankind in this century. The knowledge of the physical laws and features that govern each component of the hydrologic cycle has an increasing importance. Within the hydrologic cycle, the evaporation process inherent to the different surfaces present on the earth needs to be properly understood, so as to achieve a sustainable development of natural resources. Particularly, the determination of consumptive use of water by crops and other surfaces at a regional scale is fundamental in understanding whether resources management is adequate or not. Irrigated agriculture is the largest consumer of water in river basins, and water savings upstream can lead to additional water developments downstream in the basin (Allen *et al.*, 2002).

Over the past decades there have been efforts to evaluate evapotranspiration (ET) over large areas from primarily remotely sensed data. Here, the term ‘large area’ refers to a regional scale characterized by regional-scale climatic characteristics (Bastiaanssen, 1995). Reviews of remote sensing algorithms to estimate evapotranspiration were presented in Kustas and Norman (1996) and Bastiaanssen (1998). Basically, there are three main approaches: a) semi-empirical and statistical methods, b) analytical, and c) numerical approaches. In the first approach, the total daily ET is estimated from remotely sensed one-time-of-day radiometric surface temperature measurements, air temperature and, usually, some correlation with a remote sensed vegetation index (Jackson *et al.*, 1977; Caselles *et al.*, 1998). Analytical approaches estimate ET by combining remotely sensed spectral data with ground-based meteorological data to evaluate net radiation (R_n), sensible heat (H), and soil heat flux (G), and obtain latent heat flux (LE) as the residual from the energy balance (Kustas *et al.*, 1990; Bastiaanssen, 2000; Granger, 2000). The third class uses models that simulate the water and energy balance by solving numerical equations for heat and mass transfer, combining remotely sensed data and ground-based information (Choudhury and DiGirolamo, 1988). The major advantage of applying remote sensing is that the water consumed by the soil-water-vegetation system can be derived directly without the need for quantifying other complex hydrological processes. However, the majority of methods require calibrations that involve ground measurements and local calibration. The ground-based calibrations are used to predict ET for areas located near where the

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TABLE I
AVERAGE VALUES OF MEASURED WEATHER PARAMETERS AND CALCULATED ET$_O$ "BIOLÓGICA LOS LLANOS" (1968-2002)

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dec	Annual
Mean T (°C)	27.8	28.5	29.5	29.7	28.2	26.7	26.2	26.4	26.6	27	27.4	27.4	27.6
Max. T (°C)	34.4	35.3	36	35.6	33.2	31.3	30.9	31.1	31.8	32.5	33.1	33.8	33.3
Min. T (°C)	21.7	22.1	23.7	24.4	23.6	22.7	21.9	22	22.2	22.3	21.7	21.6	22.5
Mean RH (%)	60	57	54	57	70	77	79	81	80	78	75	66	70
Max RH (%)	92	90	86	90	94	95	95	96	96	96	97	95	94
Min RH (%)	30	30	28	30	37	43	43	45	45	41	38	33	37
Sunshine (hr)	9	9.3	8.7	7.1	6.3	5.9	6.2	6	6.7	7.4	8.4	8.8	7.5
WS (m/s)	3.4	3.3	3.6	3.0	2.4	2.0	1.8	1.7	1.7	1.9	2.4	2.8	2.5
Precip. (mm)	2.1	3.5	8.6	65	177.6	231	222.1	246.1	163.5	128.7	59.4	11.1	1319
ET$_o$* (mm/d)	6.6	7.0	7.6	6.7	5.5	4.7	4.6	4.5	4.7	5.0	5.3	5.8	5.3

T: air temperature, RH: relative humidity, WS: wind speed. * ET$_o$: grass reference evapotranspiration calculated by FAO-56 procedure.

measurements were taken. This fact makes many current methods site-specific and far for being routinely applied.

Within the most promising approaches currently available to estimate ET, the Surface Energy Balance Algorithm for Land (SEBAL) has been designed to calculate the energy balance components, at both local and regional scale, with minimum ground data (Bastiaanssen *et al.*, 1998). SEBAL has been tested under several irrigation conditions in Egypt, India, Sri Lanka, Pakistan and Argentina to diagnose the uniformity in crop consumptive use, monitor crop water stress, and evaluate irrigation performance (Bastiaanssen, 2000). Because it requires a minimum amount of inputs, SEBAL has a great potential for use in developing countries where policies for water management are generally inadequate and ground information is scarce.

The overall intent of this research was to explore means for generating ET maps for irrigated lands in Venezuela, where lack of ground information is commonplace. A remote sensing model is required to be routinely applied as a tool for providing both historical and near-real time ET for modeling of groundwater, solving water rights disputes, and performing a better management of the water resources of the area.

Study Area

The Río Guárico Irrigation System is a hydraulic infrastructure for irrigation located in the Guarico State, in Venezuela, 8.5-9ºN and 67.18-67.45ºW and ~100masl. The system is in operation since 1956. A large water reservoir (the Calabozo dam, with a water surface of ~12541ha) stores the water from the Guárico River and provides for irrigation of ~60000ha, even though the system was originally projected to cover 110000ha (Montilla, 1995). Rice is the main crop grown in the area and the usual size of a production unit is 20ha per producer. Figure 1 shows the study area and its relative situation in Venezuela.

The irrigation period starts at the end of the rainy season, between Oct and Nov, and ends between Apr and May. Despite water availability, rice yields have been significantly lower than international averages for irrigated crops, due to the lack of an appropriate water management and distribution in this irrigation system. Rice yields in the area are around 4ton/ha, while the literature reports that one can expect yields as high as 6 to 8ton/ha with controlled irrigation (Doorenbos and Kassam, 1980). The length of the growing cycle for rice in the area is 140 days. Total depth of irrigated water currently used is around 1940mm (average of 14mm/d), a value that is much larger than the crop water requirements (Montilla, 1995). This fact indicates that the water management is inefficient and that there is an authentic need for a better estimation of the actual quantity of water to be applied to crops in the area.

Table I shows a summary of climate characteristics of the study area for the period 1968-2002, using data collected at the "Biológica Los Llanos" weather station. Annual precipitation is 1319mm, but total precipitation for Jan to Apr is less than 80mm, which indicates the requirement of irrigation to sustain agriculture. Peak precipitation occurs between Jun and Aug (>220mm each month). Monthly mean air tempera-

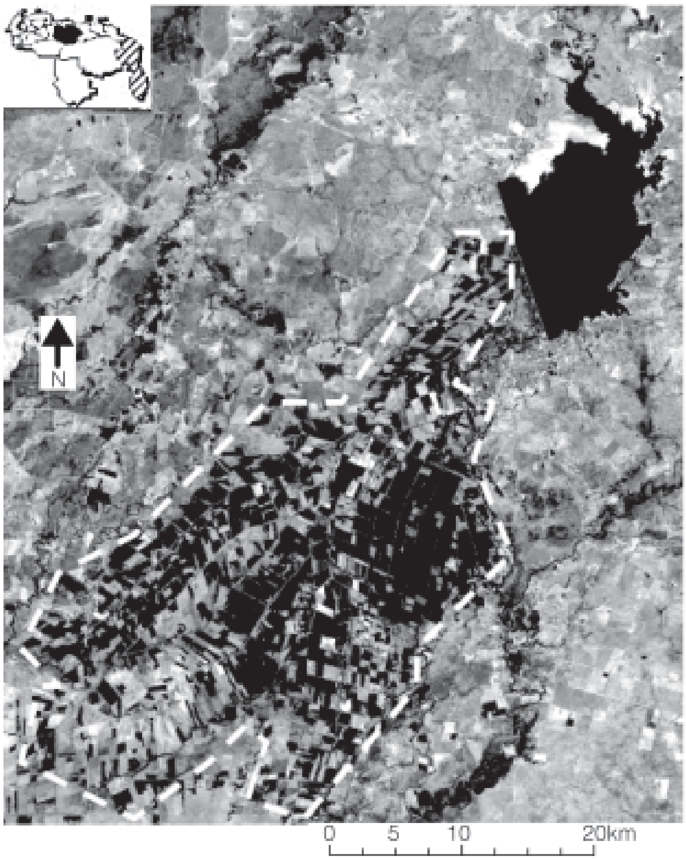

Figure 1. LANDSAT 7 image (03/14/2001), showing the irrigation system and the Río Guárico Reservoir. Vegetated areas are shown in darker colors; bare soils in gray and bright colors. The Calabozo water reservoir can be seen in the upper right side of the image (black color). The dashed white line defines the main irrigated area. The small picture on the upper left shows the relative location of the Guárico State in Venezuela.

ture is relative constant during the year with a maximum between Mar and Apr (29.5 and 29.7ºC) and with a minimum of 26.2ºC in Jul. In addition, Table I includes values of monthly grass reference ET$_o$, calculated using FAO-56 procedure (Allen *et al.*, 1998). Peak reference ET is in March (7.6mm/d).

Materials and Methods

Model description

To overcome the dependency of remote sensing for in-situ measurements, the Surface Energy Balance Algorithm for Land (SEBAL) was proposed by Bastiaanssen (1995). The advantage of the SEBAL procedure is that it allows the estimation of evapotranspiration at the regional scale using a small amount of ground based inputs. A self-calibration procedure is applied in SEBAL that "trains" the surface energy balance by defining it at two "anchor" pixels.

SEBAL is based on the energy balance, which gives it a robust theoretical framework. The original SEBAL (Bastiaanssen *et al.*, 1998) makes use of some semi-empirical equations in order to keep the model as operational as possible (less input requirements). Examples of these equations are functions that estimate soil heat flux from albedo and surface temperature, and surface roughness from vegetation indices. Although tested and validated in a variety of environments, these empirical equations may need further calibration when applied to a new environment like irrigated areas in Venezuela. Fortunately, the flexibility and open framework of SEBAL allows the modification of its components if better functions are available.

Theoretical basis

SEBAL uses digital imagery data collected by a remote-sensing satellite measuring visible, near-infrared and thermal infrared radiation. The principles and steps needed to apply SEBAL to estimate evapotranspiration are described in Bastiaanssen (1995), Bastiaanssen *et al.* (1998), and Trezza (2002).

Evapotranspiration (ET) is computed as a residual of the energy balance equation on a pixel-by-pixel basis:

$$LE_{pixel}=\lambda*ET_{pixel}=R_{n\ pixel}-H_{pixel}\ -G_{pixel} \qquad (1)$$

where LE$_{pixel}$: latent heat flux for the pixel, ET$_{pixel}$: pixel ET, λ:latent heat of vaporization, and R$_{n\ pixel}$, H$_{pixel}$, and G$_{pixel}$ are the net radiation, sensible heat flux and soil heat flux for each pixel, respectively.

SEBAL calculates net radiation as the radiation balance between net shortwave and net longwave radiation at the surface, which can be written as

$$R_n = (1-\alpha)R_{si} + R_{li} + R_{lo} + (1-\varepsilon_o)R_{li} \qquad (2)$$

where α: surface albedo for shortwave radiation, R$_{si}$: incoming shortwave radiation, R$_{lo}$: longwave (thermal) radiation emitted by the surface, R$_{li}$: longwave radiation emitted by the atmosphere that reaches the surface, e$_o$: thermal emissivity of the surface, and $(1-\varepsilon_o)R_{li}$: amount of R$_{li}$ that is reflected back by the surface.

The empirical equation proposed by Bastiaanssen (2000) to compute the soil heat flux for any condition of vegetation cover and type of soil is

$$\frac{G}{R_n}=\left[\frac{T_s}{\alpha}\left(0.0038\alpha+0.0074\alpha^2\right)\left(1-0.98\,NDVI^4\right)\right] \qquad (3)$$

where G: soil heat flux, α: surface albedo, T$_s$: surface temperature (ºC), and NDVI: normalized difference vegetation index. NDVI is calculated from the Landsat band 4 and band 3 reflectances (ρ_4 and ρ_3, respectively) as NDVI= $(\rho_4-\rho_3)/(\rho_4+\rho_3)$; NDVI values normally range from 0 to 1, where a NDVI >0.7 represents full cover conditions for most crops.

After calculating R$_n$ and G, the calculation of the sensible heat flux H is required to obtain the parameters that will allow the computation of ET as a residual from the energy balance. The aerodynamic transfer of heat to air, H, is predicted using the following equation (Brutsaert, 1982):

$$H=\rho Cp\frac{T_{aero}-T_a}{r_{ah}} \qquad (4)$$

where ρ: air density, a function of atmospheric pressure; Cp: specific heat capacity of air; T$_{aero}$: aerodynamic surface temperature; T$_a$: reference height air temperature; and r$_{ah}$: aerodynamic resistance to sensible heat transport between the surface and the reference height. Accurate application of Eq. 4 from satellite data is hindered by the difficulty in estimating aerodynamic surface temperature (T$_{aero}$) accurately, due to uncertainty in atmospheric attenuation, contamination and radiometric calibration of the sensor, and because radiometric temperature T$_s$, as measured by satellite, deviates from aerodynamic temperature T$_{aero}$ that drives the heat transfer process.

In SEBAL, instead of T$_{aero}$, the reference temperature is taken to be T$_1$, an air temperature located at height z$_1$ close to the surface (z$_1$= 0.1m). An upper height is taken at a height z$_2$= 2m and its corresponding temperature is called T$_2$. The difference between T$_1$ and T$_2$ is referred as the "near surface air temperature difference" or dT. The sensible heat flux is then defined as

$$H=\rho Cp\frac{dT}{r_{ah}} \qquad (5)$$

where r$_{ah}$: aerodynamic resistance to heat transport between z$_1$ and z$_2$, and dT: air temperature difference between the two heights z$_1$ and z$_2$ above the surface, dT= T$_1$-T$_2$.

To determine the value of dT for each pixel, the SEBAL procedure assumes the existence of a linear relationship between dT and the surface temperature T$_s$:

$$dT = a\ T_s + b \qquad (6)$$

where T$_s$: radiometric surface temperature, and "a" and "b": empirical coefficients obtained from the so-called "anchor" pixels (Bastiaanssen, 1995). The assumption implicit in the SEBAL is that hot areas (with large thermal emittance) create a higher vertical dT than cold surfaces, and that this relationship is linear.

In summary, SEBAL is applied following these steps: a) calculation of R$_n$ for each pixel from Eq. 2; b) calculation of G for each pixel from Eq. 3; c) definition of the dT function (Eq. 6) using dT and T$_s$ obtained from the two "anchor" pixels; d) calculation of dT for each pixel from the pixel surface temperature, using Eq. 6; e) calculation of H for each pixel from Eq. 5; and f) calculation of LE (ET) from Eq.1. All energy balance fluxes (R$_n$, G, H, and LE) represent instantaneous fluxes corresponding to the instant when the satellite image was taken. Complete details for each step are explained in Bastiaanssen *et al.* (1998).

SEBAL modifications made for the study area

The original SEBAL model was modified to be adapted to the limited weather and ground information existing for the study area, as well as the predominant crop cultivated in it. As already mentioned, SEBAL uses a self-calibration procedure that controls the surface energy balance by defining it at two "anchor" pixels.

In general, the anchor pixels represent conditions of extreme evaporative behavior within the image, so-called the "cold (wet)" pixel and the "hot (dry)" pixel. The cold pixel is located in the image as a pixel having one of the lowest surface temperatures, which is taken in SEBAL as indication of wetness. In the "cold" pixel evaporation, most of the available energy (R_n-G) is assumed to be consumed by evapotranspiration, so that sensible heat flux (H), and consequently dT are both assumed to be near zero. The "dry" pixel is represented by a pixel with high temperature, which is taken in SEBAL as indicator of lack of surface moisture, where evaporation is near zero so that all the available energy is converted essentially into sensible heat. Near surface air-temperature difference, dT, is then calculated from Eq. 5 for the two extreme conditions. Then, a pair of dT and T_s values allows the definition of coefficients a and b for Eq. 6.

In SEBAL, the cold pixel is generally taken from a pixel located in deep water, and dT and H are assumed to be zero; therefore H_{cold}= 0 so that dT_{cold}= 0 (Eq. 5). The hot pixel is located in an area that shows high surface temperature where zero evaporation can be assumed; therefore H_{hot}= R_{nhot}-G_{hot} and dT_{hot} is calculated from Eq. 5 (Bastiaanssen, 2000).

In this work, the two anchor pixels were re-defined. For the cold pixel, a pixel located at a full-cover rice area was selected. The hot pixel was located at an agricultural bare soil area. Therefore, the dT coefficients (for Eq. 6) were calculated as

$$a=\frac{dT_{hot}-dT_{cold}}{T_{s\,hot}-T_{s\,cold}} \quad (7) \text{ and}$$

$$b=dT_{cold}\ -\ a\ T_{s\,cold} \quad (8)$$

where dT_{hot} and dT_{cold}: dT values for the hot and cold pixels, respectively; $T_{s\,hot}$ and $T_{s\,cold}$: corresponding values of surface temperature. The values of dT for the cold and hot pixels were calculated using the following equations, based on Eq. 5:

$$dT_{hot}=\frac{H_{hot}r_{ah}}{\rho Cp}=\frac{(R_n-G-\lambda*ET)_{hot}r_{ah}}{\rho Cp} \quad (9)$$

$$dT_{cold}=\frac{H_{cold}r_{ah}}{\rho Cp}=\frac{(R_n-G-\lambda*ET)_{cold}r_{ah}}{\rho Cp} \quad (10)$$

where H_{hot}, $R_{n\,hot}$, ET_{hot} and G_{hot}: values of sensible heat, net radiation, evapotranspiration, and soil heat flux, respectively, for the hot pixel; H_{cold}, $R_{n\,cold}$, G_{cold}, and ET_{cold}: values of sensible heat, net radiation, soil heat flux, and evapotranspiration, respectively, for the cold pixel. Guidelines for proper selection of both the cold and hot pixel can be found in Bastiaanssen (1995), Trezza (2002), and Allen *et al.* (2006).

ET in the cold pixel (ET_{cold}) was defined using the single crop coefficient approach of FAO-56 (Allen *et al.*, 1998):

$$ET_{cold} = ET_c = K_c\ ET_o \quad (11)$$

where ET_c: crop evapotranspiration, ET_o: grass reference evapotranspiration, and K_c: crop coefficient. The value of ET_o was calculated using the FAO Penman-Monteith equation of FAO-56 (Allen *et al.*, 1998):

$$ET_o=\frac{0.408\Delta(R_n-G)+\gamma\frac{C_n}{T+273}u_2(e_s-e_a)}{\Delta+\gamma(1+0.34u_2)} \quad (12)$$

where ET_o: reference evapotranspiration ($mm{\cdot}d^{-1}$ for daily steps or $mm{\cdot}h^{-1}$ for hourly steps), R_n: net radiation at the crop surface ($MJ{\cdot}m^{-2}{\cdot}d^{-1}$ for daily steps or $MJ{\cdot}m^{-2}{\cdot}h^{-1}$ for hourly steps), G: soil heat flux density ($MJ{\cdot}m^{-2}{\cdot}d^{-1}$ or $MJ{\cdot}m^{-2}{\cdot}h^{-1}$), T is the mean daily (or hourly) air temperature (ºC) at 2m height, u_2: is the average daily (or hourly) wind speed ($m{\cdot}s^{-1}$) at 2m height, e_s: saturation vapor pressure (kPa), e_a: actual vapor pressure (kPa), Δ: slope vapor pressure curve ($kPa{\cdot}{}^{o}C^{-1}$), γ: psychometric constant ($kPa{\cdot}{}^{o}C^{-1}$), Cn= 900 for daily steps and Cn= 37 for hourly steps. Details for calculations on Eq. 12 are found in Allen *et al.* (1998).

The hypothesis here is that the assignment of the calculated evapotranspiration (ET_c) to the cold pixel (Eq. 11) will produce a better approximation of the real ET that takes place in the study area, and serve as a self-calibration of the image. ET_c is calculated from ET_o (Eq. 12), which incorporates the meteorological information of the site and from the crop coefficient (K_c), which is related to the actual crop that is available in cold pixel candidates inside the study area. This assumption is similar to the one presented by Trezza (2002) and by Allen *et al.* (2006) for the model METRIC, where the cold pixel is taken from an alfalfa field, and where ET_{cold} is approximated to the alfalfa reference ET. Results by Trezza (2002) and Allen *et al.* (2005) suggested the advantages of this modification by comparing ET estimates with ET measurements from lysimeters at Kimberly, Idaho, USA.

To define the evapotranspiration of the hot pixel (ET_{hot}), a daily water balance for the top soil surface such as that of FAO-56 (Allen *et al.*, 1998) is run for a bare soil condition for the image date to confirm that ET= 0 or to supply a nonzero value if there is evaporation from antecedent precipitation.

Extrapolation of instantaneous ET to daily ET values

The values of ET derived from SEBAL represent instantaneous values corresponding to the time at which the satellite image was taken. However, instantaneous ET values are not very useful inputs for many hydrological and ecological applications where daily, monthly, and seasonal values are commonly needed. To estimate the 24h ET for the day of the image, SEBAL uses an approach based on the self-preservation theory of daytime fluxes, which states that the ratio between the latent heat flux and the available energy (R_n-G) remains fairly constant during the day (Bastiaanssen *et al.*, 1998). This ratio between LE and R_n-G is termed the evaporative fraction (EF).

For this application, daily ET (ET_{24}) was estimated by assuming that the instantaneous crop coefficient (K_c), computed at image time, is the same as the average K_c over the 24h period. Therefore, the value of ET_{24} for each pixel is calculated as

$$K_C=\frac{ET}{ET_o}=\frac{ET_{24}}{ET_{o\,24}}\Rightarrow ET_{24}=K_C*ET_{o\,24} \quad (13)$$

where K_c, ET, and ET_o: instantaneous values of crop coefficient, actual and reference evapotranspiration, for the time when the satellite image was taken; and ET_{24} and $ET_{o\,24}$: corresponding daily values (24h) of actual and reference ET. The hypothesis here is that the relationship between actual and reference ET remains relatively constant during the daytime as demonstrated in various experiments (Trezza, 2002; Allen *et al.*, 2005). In other words, this approach assumes that the crop coefficient (K_c) remains constant during the day, which is reasonable if one takes into account that both actual and reference ET might have similar response to the variation of the weather parameters.

Meteorological and satellite data

Meteorological data in Venezuela is scarce. In most cases only monthly data is available, which strongly constrains the application of any remote sensing model. In this study, information provided by the "Biológica Los Llanos" meteorological station was used. The station is located a few km from the study area and routinely provides daily meteorological data needed for the SEBAL processing (air temperature, relative humidity, wind speed, solar radiation and precipitation). Hourly meteorological data is not routinely reported so that it was obtained directly at the weather station site. For the application of the remote sensing model, hourly meteorological data was used to calculate hourly values of ET_o (from Eq. 12) and estimate the value of ET_o for the satellite overpass time (14:10 GMT). Daily meteorological data is used to calculate daily ET_o ($ET_{o\,24}$) to be used in Eq. 16.

With regard to satellite data, a LANDSAT 7 ETM+ image corresponding to March 14, 2001, path 4, row 54 was used. Visible bands (bands 1,2,3,4,5,7) were used for albedo (α), and vegetation index calculation (NDVI). Thermal band (band 6) was used for surface temperature (T_s) and sensible heat (H). Spatial resolution is 30×30m on the visible bands and 60×60m on the thermal band.

Application of the SEBAL model

The SEBAL model was applied to the LANDSAT 7 ETM+ image corresponding to March 14, 2001 to produce estimates of ET at 30×30m resolution. The software ERDAS-IMAGE 8.7 (ESRI) was used for image manipulation and the SEBAL model was coded in ERDAS model maker. The original SEBAL model was modified to be adapted to the limited weather and ground information existing for the study area. As discussed before, for the study area the two anchor pixels were defined as

Cold pixel. The cold pixel was taken in an agriculture area, cultivated with paddy rice, having low temperature and high NDVI. The low temperature was taken as an indication of an adequate irrigation and the high NDVI was considered as an indicative of maximum cover by rice. In this pixel, ET was assumed to be the value obtained as the product of reference ET (Eq. 12) and the corresponding crop coefficient for rice for complete cover, using Eq. 11. The value of the crop coefficient was taken as that reported in FAO-56 K_c value for full cover paddy rice, which is K_c= 1.2.

Hot pixel. The hot pixel was taken in a bare soil located in an agricultural area. A daily surface soil water balance was run for bare soil conditions using daily values of precipitation and general soil characteristics for the area. The water balance is based on the FAO-56 approach (Allen *et al*., 1998). There was no rain during the months of Jan, Feb and Mar 2001, as reported by the "Biológica Los Llanos" weather station. Results of the water balance indicated that ET= 0 for bare soil conditions; therefore it was assumed that ET_{hot}= 0.

Results and Discussion

Table II shows a summary of the information related to the cold and hot pixels. Instantaneous value of ET (ET_{cold}) was calculated as ET= 0.75mm/h for the cold pixel using Eq. 11, for the satellite overpass time (14:10 GMT). Daily ET for the cold pixel was calculated as ET= 8.0mm/d. Table II also includes values of net radiation (R_n), soil heat flux (G), and sensible heat flux (H) for both pixels; these fluxes are instantaneous values corresponding to the overpass time.

TABLE II
INSTANTANEOUS AND DAILY PARAMETERS AND FLUXES DURING THE LANDSAT OVERPASS AT THE WET AND DRY PIXELS FOR MARCH 14, 2001

Parameter	Cold (wet) Pixel	Hot (dry) Pixel	Observation
Surface	full cover rice	bare soil	From agricultural area
K_c	1.2	0	Taken from FAO-56, paddy rice (cold); and defined from surface water balance (hot)
ET (mm/h)	0.75	0.0	Instantaneous ET, at satellite time, calculated from Eq. 12
ET_{24} (mm/d)	8.0	0.0	Daily ET calculated from Eq.12
NDVI	0.752	0.163	Calculated from Landsat band 4 and 3
Albedo	0.219	0.158	Calculated from Landsat bands 1,2,3,4,5,7
T_s (K)	295.5	308.2	Calculated from Landsat band 6
R_n (W/m^2)	602.6	477.3	Result from SEBAL at satellite time
G (W/m^2)	50.4	96.2	Result from SEBAL at satellite time
H (W/m^2)	42.2	381.1	$H= R_n - G - LE$
LE (W/m^2)	510.0	0.0	Instantaneous ET, expressed in W/m^2

Figure 2 shows the evapotranspiration map corresponding to the date 03/14/2001 for the entire Río Guárico Irrigation system and surrounding areas. ET resolution is 30×30m. ET values range between near 0 (bare soil) to 8.2mm (full-cover rice) on the irrigation system. The ET map also includes values for areas near the irrigation system that include natural vegetation, bare soil and riparian vegetation. All of these ET values are important for the hydrological balance of the area as well as for groundwater modeling.

A summary of ET for the entire image is shown in Table III. Evaporation in the reservoir ranged from 3.96 to 4.60mm, with an average ET value of 4.3mm. Total evaporation in the reservoir, with a total surface area of 12541ha, was estimated as 543.2×10^{3}m^3, value that represents the evaporation losses during the day considered. ET values in the agricultural area served by the irrigation system (defined in Figure 1) ranged from 0 (bare soil) to 8.2mm that represents ET occurring in full-cover rice fields. The average ET value for the agricultural areas was 4.43mm. Total ET for the 64298ha of agricultural lands was 2849.7×10^{3}m^3.

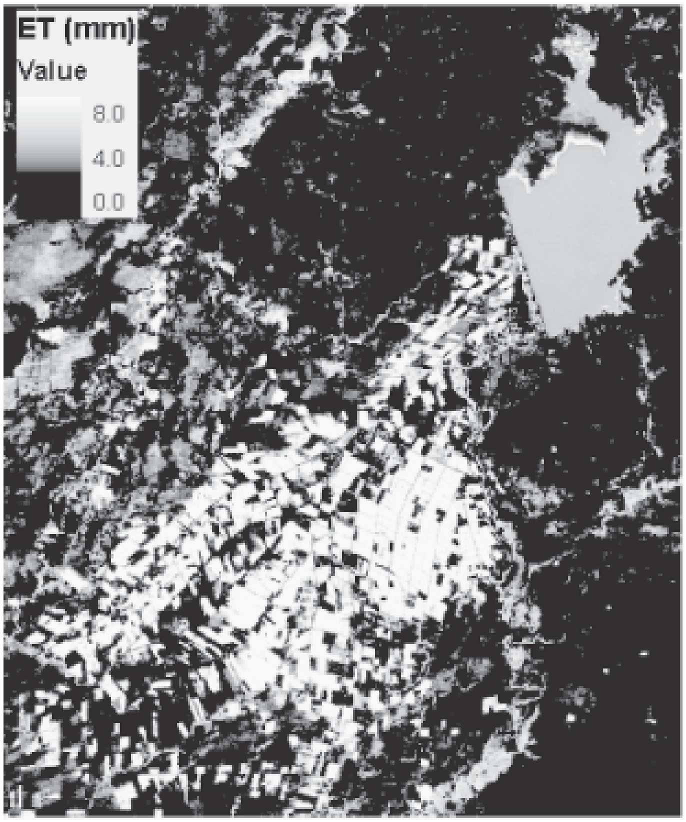

Figure 2. Daily evapotranspiration (ET) map for March 14, 2001, for the irrigation system, the reservoir and surrounding areas. ET map has a spatial resolution of 30m x 30m.

TABLE III

VALUES OF TOTAL EVAPOTRANSPIRATION FOR THE RESERVOIR AND IRRIGATED AREAS CORRESPONDING TO MARCH 14, 2001

Surface	Min ET (mm)	MaxET (mm)	Average ET (mm)	SD of ET (mm)	Area (ha)	Total ET (m^3 x 10^3)
Calabozo Dam (reservoir)	3.96	4.60	4.33	0.09	12540.94	543.2
Irrigated Crops	0.01	8.20	4.43	2.32	64297.8	2849.7
Total						3392.9

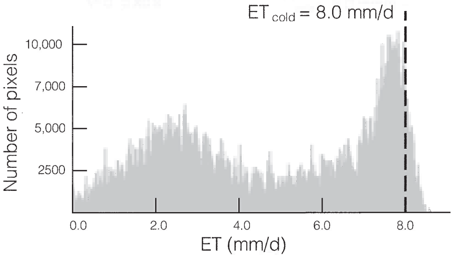

Figure 3. Histogram of daily ET for the irrigated area (defined on Figure 1) for March 14, 2001. A total of 2141502 pixels were considered for the statistics. Each pixel represents an area of 900m^2 (0.09ha).

According to Table III, the total water use during Mar 14, 2001, by evaporation in the reservoir and evapotranspiration in the irrigated areas was 3392.9×10^{3}m^3. This value represents basic information for the water management of the irrigation system.

Figure 3 depicts the histogram of the values of ET in the irrigated area (defined in Figure 1). Maximum values of ET were controlled by the ET assigned to the cold pixel (ET_{cold}). Note that some pixels resulted in ET values slightly greater than ET_{cold}, because ET_{cold} represents the ET for an average full-cover and well-irrigated condition, and therefore it is expected that some pixels could have more ET than the cold pixel, for example in areas where irrigation was occurring during the satellite overpass time. From the histogram it can be seen that the irrigated surfaces are aggregated in various groups. A group of pixels shows ET values corresponding to full cover and well irrigated conditions. Another group has most of the pixels grouped at an ET value of around 2.0mm/d. This fact indicates differences in both water and crop management as well as in crop growing stages.

The histogram in Figure 3 demonstrates the importance of the cold pixel hypothesis for the calibration of the entire image, because the cold pixel selection "controls" the tendency of the maximum values of ET. For this reason, both the right selection of the cold pixel, as well as the right calculation of ET_{cold} are critical in order to obtain ET estimations as realistic as possible. The histogram suggests that the model results are very sensitive to the cold pixel selection. On the other hand, if the cold pixel is well selected and ET for full cover conditions is well calculated, then one can expect to obtain the best estimates of ET for the area using remote sensing. The selection of the hot pixel is also important because it controls and defines the lower limit of the ET values for the area.

Conclusions and Recommendations

The overall intent of this research was to explore a way for generating ET maps for the Río Guárico Irrigation System in Venezuela, an area with more than 60000ha of irrigated land cultivated mainly with rice. An operational remote sensing model is desired for routine application by the system managers as a means for predicting ET over this important area in order to perform a better management of the water resources of the region.

The Surface Energy Balance Algorithm for Land (SEBAL) was selected as the basis to develop a model that can be adapted to the prevailing conditions of the study area. Two major modifications of the original SEBAL were made to improve prediction of several components of the surface energy balance. The main modification was the redefinition of the two "anchor" points (cold and hot pixels) to improve prediction of ET in agricultural areas, and to tie ET values to the local weather conditions of the region. In the original SEBAL cold and hot pixels are taken from water and extremely hot surfaces, whereas in this study the cold pixel was taken from a well-watered full cover rice crop and the hot pixel was taken from dry agricultural bare soils. ET for the cold pixel was estimated using FAO-56 methodology (Allen *et al.*, 1998). The advantage of calculating ET_{cold} from ET_c (Eq. 11) is that it ties the prediction of ET at the cold pixel to a well validated equation (Eq. 12) that considers local wind, solar radiation, and humidity conditions (Allen *et al.*, 2005). ET_o integrates the effect of local weather parameters in the ET process, so that the ET at the cold pixel will be representative of the weather conditions of the study area. In addition, the calculation of ET_{cold} from Eq. 11 incorporates the crop coefficient (K_c), which provides a more realistic approximation of the ET that occurs from a specific crop. A second modification was the use of the crop coefficient for extrapolation of instantaneous ET values to daily ET.

The main limitation for the model application was the availability of weather data. Fortunately, the weather station used in this study, "Biológica Los Llanos", provides daily information, which is not the case for most agricultural areas in Venezuela, where only monthly data is available. Besides, the use of FAO-56 methodology for estimation of ET in the cold pixel makes the proposed model dependent on the accuracy of the crop coefficient value and the quality of the weather information for the estimation of the reference ET.

The proposed methodology allowed the estimation of water use for the irrigation system and water reservoir for Mar 14, 2001. Evaporation in the reservoir was estimated as 543.2×10^{3}m^3. This value allows the prediction of evaporation losses in the reservoir if this methodology is used routinely. Water consumption in the irrigated lands was estimated as 2849.7×10^{3}m^3 by spatially integrating the ET values for the entire area. These values represent critical information for the management of water in the reservoir. However, it is important to point out that these values represent ET for a single day. To extrapolate daily values to monthly and seasonal ET, the processing of several images during the growing season is required, as well as a mean to integrate the daily ET into seasonal values.

From the analysis described it is concluded that the application of this modified SEBAL model is promising for estimating ET in agricultural areas in Venezuela. However, a better distribution of meteorological information is needed. SEBAL has been developed in such a way that the need for extensive measurements is partly eliminated, but there is a strong need for some daily weather information in order to tie the model to the climatologic conditions of the area. If weather information is missing, then the original SEBAL of Bastiaanssen *et al.* (1998) is recommended.

With regard to satellite data, a LANDSAT image was used in this study. Because of the high cost of LANDSAT imagery, the proposed methodology can encounter problems to be applied in a routinely basis in Venezuela. A real alternative is to use TERRA-MODIS imagery, which are free of cost and includes all the bands needed for SEBAL application. Even though spatial resolution is coarser in TERRA-MODIS imagery (visible bands have a 250×250m resolution and thermal bands are 1000×1000m), this kind of satellite data might be sufficient for water management purposes on large irrigation systems.

The value of the SEBAL model to estimate evapotranspiration for large areas in Venezuela in an operational manner is recognized, but more validation work is needed to refine several components of SEBAL that introduce uncertainties into the results. Also, there is a critical need for meteorological information in agricultural areas in Venezuela in order to make the proposed model feasible for routine use in operational irrigation.

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ESTIMACIÓN DE LA EVAPOTRANSPIRACIÓN CON UN MODELO DE TELEDETECCIÓN PARA EL MANEJO DEL AGUA EN UN SISTEMA DE RIEGO EN VENEZUELA

Ricardo Trezza

RESUMEN

Este trabajo explora la factibilidad de utilizar un modelo de balance de energía para la estimación de evapotranspiración a través de datos satélitales en un área bajo riego, el sistema de riego Río Guárico, en Venezuela. Las aguas del Río Guárico son almacenadas en una gran represa para proveer de agua a un área de ~60000ha, donde el arroz es el principal cultivo. A pesar de existir suficiente agua, el potencial agrícola de la zona se ha visto limitado por la falta de un manejo adecuado del sistema de riego. El modelo utilizado en este estudio es SEBAL (Algoritmo para el Balance de Energía Superficial), el cual es un modelo procesador de imágenes para calcular evapotranspiración (ET) por diferencia en el balance energético, desarrollado en Holanda y aplicado en numerosos países en desarrollo. SEBAL utiliza información registrada por el Mapeador Temático (TM) de LANDSAT u otros satélites que registren radiación visible, infrarroja cercana y térmica. La principal ventaja de SEBAL es que requiere de una cantidad mínima de información de campo. El modelo original fue modificado y adaptado para ser utilizado a las condiciones específicas del área de estudio, utilizando la metodología de FAO-56. Los resultados sugieren que SEBAL puede ser considerado como un método viable para estimar ET en tierras regadas que posean limitación de información, lo cual es común en Venezuela.

ESTIMAÇÃO DA EVAPOTRANSPIRAÇÃO COM UM MODELO DE TELEDETECÇÃO PARA O MANEJO DA AGUA EM UM SISTEMA DE IRRIGAÇÃO NA VENEZUELA

Ricardo Trezza

RESUMO

Este trabalho explora a factibilidade de utilizar um modelo de balance de energia para a estimação de evapotranspiração através de dados satelitais numa área sob irrigação, o sistema de irrigação Rio Guárico, na Venezuela. As aguas do Rio Guárico são armazenadas em uma grande represa para fornecer agua a uma área de ~60.000ha, onde o arroz é o principal cultivo. Apesar de existir suficiente agua, o potencial agrícola da zona se tem visto limitado pela falta de um manejo adequado do sistema de irrigação. O modelo utilizado neste estudo é SEBAL (Algoritmo para o Balanço de Energía Superficial), o qual é um modelo processador de imagens para calcular evapotranspiração (ET) por diferença no balance energético, desenvolvido na Holanda e aplicado em numerosos países em desenvolvimento. SEBAL utiliza informação registrada pelo Mapeador Temático (TM) de LANDSAT ou outros satélites que registrem radiação visível, infravermelho proximal e térmica. A principal vantagem de SEBAL é que requer de uma quantidade mínima de informação de campo. O modelo original foi modificado e adaptado para ser utilizado nas condições específicas da área de estudo, utilizando a metodologia de FAO-56. Os resultados sugerem que SEBAL pode ser considerado como um método viável para estimar ET em terras irrigadas que possuam limitação de informação, o qual é comum na Venezuela.