SEBAL Model with Remotely Sensed Data to Improve Water-Resources Management under Actual Field Conditions

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Abstract: Water management emphasis tends to shift from supply augmentation to limiting water consumption. Spatio-temporal information on actual evapotranspiration (ET) helps users to better understand evaporative depletion and to establish links between land use, water allocation, and water use. Satellite-based measurements, used in association with energy balance models, can provide the spatial distribution of ET for these linkages. This paper describes the major principles of the Surface Energy Balance Algorithm for Land (SEBAL) and summarizes its accuracy under several climatic conditions at both field and catchment scales. For a range of soil wetness and plant community conditions, the typical accuracy at field scale is 85% for 1 day and it increases to 95% on a seasonal basis. The accuracy of annual ET of large watersheds was found to be 96% on average. SEBAL has been applied in more than 30 countries worldwide, and the 26 research studies that were conducted over the past 10 years are now gradually being replaced by application studies (17 studies finished). A short case study in the Yakima River basin (Washington State) is presented as new material to demonstrate how ET from remote sensing can be used for evaluating water conservation projects.

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Introduction

Competition for water in agriculture increases each year, and water is being transferred from agriculture to nonagricultural uses. Because water resources have become scarcer in relation to demand, those countries that already plan allocation of water in an organized fashion through the administration of water-right systems have become increasingly aware that water rights defined in terms of "entitlements to divert" are less useful than water rights defined as "entitlements to consume." Although the two are intrinsically related, managing consumption seems to take priority for managing allocation. This paradigm shift (Perry 1999), promotes an approach that links sources, uses, losses, and reuses by different land-use categories and environmental systems present within river basins.

Understanding the temporal and spatial distribution of evaporative depletion is essential for managing river basins and water-supply systems. River basins typically host irrigated agriculture, rainfed agriculture, forests, native vegetation, wetlands, and riparian vegetation, all of which transmit water into the atmosphere through EvapoTranspiration (ET). Digital maps of land use and actual evaporative depletion of water resources enables policy-makers to address the issue of consumptive water use, including beneficial and nonbeneficial depletions. This is the basis for evaluating how water is consumed and understanding potential tradeoffs related to the allocation of water for agriculture and for the environment. In addition, this helps economists to place a price tag on the various components and uses (Kijne et al. 2003).

The determination of ET is not straightforward due to the natural heterogeneity and complexity of hydrological processes in catchments. The surface energy balance provides through latent heat flux a direct assessment of actual ET. The soil-water balance can then be circumvented for the assessment of ET by applying the surface energy balance.

The growing conditions for agroecosystems are not always ideal. There can be either stress from a water shortage or there can be waterlogging or salinity conditions that reduce growth and ET relative to the upper envelope of good and healthy production. The conditions in the unsaturated zone can be manipulated by man through irrigation and drainage systems, but these systems have their own limitations in adequacy, equity, and reliability (Murray-Rust and Snellen 1993; Bos et al. 1994).

A common procedure to estimate ET under nonideal conditions is the three-stage modeling procedure. In stage one, the reference ET is computed for a standard crop, such as alfalfa (Wright and Jensen 1972) or clipped grass (Doorenbos and Pruitt

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1977). The second step is to make a correction between the standard crop and the crop to be investigated through crop coefficients K_c (Wright 1982; Jensen et al. 1990). Most consumptive use studies are following this two-step approach, assuming that moisture and nutrients are at ideal levels and that management is perfect or precipitation occurs at the right time and at the right place. However, for application to actual conditions, step 3 must include a realistic soil moisture reduction term (K_s). This three-stage concept is in line with the Food and Agricultural Organization of the United Nations (FAO) dual crop coefficient approach (Allen et al. 1998; Allen 2000) and with most hydrological simulation models, e.g., HYDRUS (Simunek and van Genuchten 1994); and SWAP, (Droogers 2000) that reduce $\mathrm{ET_{pot}}$ into $\mathrm{ET_{act}}$ using soil water potential or another water availability indicator.

Instead of being modeled, ET can be measured *in situ*. Most field measurements, however, are indirect and based on equations and assumptions. Classical water balance studies that measure the vertical distribution of soil moisture must approximate the percolation flux, and any error in percolation or capillary rise will be propagated into the ET measurement. Bowen ratio surface energy balance systems depend mainly on sensor accuracy to measure small differences in air humidity. Eddy-covariance systems are frequently beset by under-measurement of heat and vapor fluxes, thereby causing energy balance closure error (Twine et al. 2000). The performance of lysimeter ET depends on the precision of installation and that vegetation is not hanging over the edge of the lysimeter (Allen et al. 1991). The accuracy of the lysimeter measurements also depends critically on how representative of the surrounding vegetation and soil moisture regime the lysimeter is. Thus, none of these *in situ* methods are completely trustworthy and all require substantial resources for their attention.

Remote sensing is an indirect ET measurement technique; it involves using a set of equations in a strict hierarchical sequence to convert the spectral radiances measured by satellites or airplanes into estimates of actual ET. The advent of the possibility to indirectly measure fundamental ET processes from satellites has radically changed our abilities in the area of water-resources management (Bastiaanssen and Bos 1999; Bastiaanssen et al. 2000; Menenti 2000; Coureault et al. 2003). Spatial coverage is available at the variety of scales needed: field, project, and basin. Temporal coverage is vastly superior at minimal cost to provide similar detail when compared to the field measurement of data.

The aim of this paper is to review the Surface Energy Balance Algorithm for Land (SEBAL) and its applications. The objective is to justify the use of the SEBAL model with remotely sensed data. It demonstrates that remote sensing is a direct method to estimate ET without a priori knowledge on soil, crop, and management conditions. SEBAL has celebrated its 10th anniversary (Bastiaanssen et al. 1992) and is now an operational instrument for targeting, monitoring, and evaluating irrigation and drainage systems (see the Appendix for a summary of potential studies).

Description of Surface Energy Balance Algorithm for Land Model

Evapotranspiration is related to the surface-energy balance, which reads as

$$R_n = G_0 + H + \lambda E \qquad (\mathrm{W \cdot m^{-2}}) \tag{1}$$

where R_n $(\mathrm{W \cdot m^{-2}})$ = the net radiation; G_0 $(\mathrm{W \cdot m^{-2}})$ = the soil heat flux; H $(\mathrm{W \cdot m^{-2}})$ = the sensible heat flux; and λE $(\mathrm{W \cdot m^{-2}})$ = the latent heat flux associated with evapotranspiration. Eq. (1) can be rewritten and expressed as latent heat flux by considering evaporative fraction Λ and net available energy $(R_n - G_0)$

$$\lambda E = \Lambda (R_n - G_0) \qquad (\mathrm{W \cdot m^{-2}}) \tag{2}$$

where

$$\Lambda = \frac{\lambda E}{R_n - G_0} = \frac{\lambda E}{\lambda E + H} \qquad (-) \tag{3}$$

The net available energy $(R_n - G_0)$ in Eq. (2) may have different timescales, from instantaneous (e.g., during a satellite overpass) to daily integrated values, or to periods elapsing between consecutive satellite measurements. Depending on the timescale chosen, different time integrations of $(R_n - G_0)$ need to be obtained. For timescales of 1 day or longer, G_0 can be often ignored and net available energy $(R_n - G_0)$ reduces to net radiation (R_n). For the daily timescale, ET_{24} can be formulated as

$$\mathrm{ET}_{24} = \frac{86{,}40010^3}{\lambda \rho_\mathrm{w}} \Lambda R_{\mathrm{n}24} \qquad (\mathrm{mm \cdot d^{-1}}) \tag{4}$$

where R_{n24} $(\mathrm{W \cdot m^{-2}})$ = the 24 h averaged net radiation; λ $(\mathrm{J \cdot kg^{-1}})$ = the latent heat of vaporization; and ρ_w $(\mathrm{kg \cdot m^{-3}})$ is the density of water. The chief assumption in SEBAL is that the evaporative fraction Λ specified in Eq. (3) remains constant during daytime hours. Experimental work has demonstrated that this holds true for environmental conditions where soil moisture does not significantly change and advection does not occur (Shuttleworth et al. 1989; Brutsaert and Sugita 1992; Nicols and Cuenca 1993; Kustas et al. 1994; Crago 1996; Franks and Beven 1997; Farah 2001).

Eq. (2) basically requires Λ, R_n, and G_0 to be known. The incoming solar radiation $K^{\downarrow}$ can be measured directly with pyranometers or can be interpreted from solar duration measurements, i.e., hours of sunshine (n). There also exist good examples of computing solar radiation from geostationary satellite data (Stewart et al. 1999). The conversion of global radiation into net radiation on timescales of days and longer periods can be achieved using a simplified formula (de Bruin and Stricker 2000)

$$R_{n24} = (1 - r_0) K_{24}^{\downarrow} - 110 K^{\downarrow}_{24} / K^{\downarrow}_{24\mathrm{exo}} \qquad (\mathrm{W \cdot m^{-2}}) \tag{5}$$

where r_0 $(-)$ is the surface albedo and $K^{\downarrow}_{exo}$ $(\mathrm{W \cdot m^{-2}})$ is the extraterrestrial radiation. The evaporative fraction was computed via the instantaneous surface energy balance residual $(R_n - G_0 - H)$, which converts Eq. (3) into

$$\Lambda = \frac{R_n - G_0 - H}{R_n - G_0} \qquad (-) \tag{6}$$

The soil heat flux G_0 is computed as a variable fraction of net radiation R_n, taking into account the presence of leaves through the Normalized Difference Vegetation Index (NDVI) and the surface temperature T_s. It is experimentally proven that warmer surfaces have a higher G_0/R_n fraction. The largest obstacle in solving Λ, though, is the estimation of H. Various research papers have been devoted to the assessment of H from the radiometric surface temperature T_0 (Sugita and Brutsaert 1990; Kalma and Jupp 1990; Brutsaert et al. 1993; Stewart et al. 1994; Troufleau et al. 1997; Chehbouni et al. 1997). However, solutions in these situations could be found only for sites that were heavily equipped to measure H, because the $H(T_0)$ relationship is not unique. The problems in the $H(T_0)$ relationship are related to the source height for the radiometric surface temperature, z_{0h}, which cannot be assessed on the basis of generic rules in heterogeneous landscapes (Carlson et al. 1995).

SEBAL computes the sensible heat flux H in an alternative way, i.e., the so-called "self-calibration" procedure. First, H is estimated at extreme dry ($H=R_n-G_0$) and wet locations ($H=0$), which are manually identified by the user on the image. This eliminates the need to install expensive *in situ* equipment to measure H. Then, by model inversion, a temperature difference ΔT that is required to match the range of H in given turbulent conditions is obtained for these two extreme dry and wet locations. The sensible heat flux H in SEBAL follows the standard Monin-Obukhov theorem for turbulent exchange processes and thermal convection (Brutsaert 1982). The sensible heat flux can be written in its most simple form as

$$H = \rho_a c_p T * u * \qquad (\mathrm{W \cdot m^{-2}}) \tag{7}$$

where ρ_a ($\mathrm{kg \cdot m^{-3}}$)=the air density of moist air; c_p ($\mathrm{J \cdot kg^{-1}\,K^{-1}}$)=the specific heat at constant pressure; $T*$ (K)=the temperature scale and $u*$ ($\mathrm{m \cdot s^{-1}}$)=the friction velocity. The temperature scale can further be formulated as

$$T* = \Delta T/[\ln(z_2/z_1) - \gamma_h(z_2,L) + \gamma_h(z_1,L)] \qquad (\mathrm{K}) \tag{8}$$

where ΔT=the vertical air temperature difference between the heights z_1 and z_2; L (m)=the Monin-Obukhov length; and γ_h=the stability correction for heat transport. Heights z_1 and z_2 are fixed in SEBAL at 0.1 and 2.0 m elevation, so that the problems originating from the roughness length for heat (z_{0h}) can be evaded (Beljaars en Holtslag 1991). A specific feature of SEBAL is that ΔT or $T(z_1)-T(z_2)$ is determined from the hot and cold pixels with assumed values of H. The surface temperature T_s is correlated then with the ΔT values found, which yields an image specific $\Delta T(T_s)$ relationship. Hence, T_s is not used to derive ΔT. The latter relationship is subsequently used to compute $T*$ during the moment of satellite overpass

$$T* = (a + bT_s)/[\ln(z_2/z_1) - \gamma_h(z_2,L) + \gamma_h(z_1,L)] \qquad (\mathrm{K}) \tag{9}$$

The values for a and b are assessed for each image or area of interest on the basis of the extremes in H and thermal infrared radiation. For this reason, SEBAL requires data from satellites having a thermal infrared channel. The coldest group of pixels having the lowest T_s values are often found in open water bodies or in well-irrigated fields. This cold pixel is used to "anchor" $\Delta T=0$, $T*=0$, which implies that $H=0$. For well-irrigated alfalfa and clipped grass fields, the reference ET can be used to estimate H under well-watered conditions (Trezza 2002; Allen et al. 2002; Tasumi 2003). The value of H can be both positive and negative, and ΔT will be computed to match the value of H at a given aerodynamic resistance (in the latter case $\Delta T=0$). The group of hottest pixels are associated with a value for ΔT such that the condition $\lambda E=0$ and $H=R_n-G_0$ are met. Morphological features on the image help to visually identify dry pixels where $\lambda E \sim 0$ holds. The value of the surface temperature is unique for every moment and location, and the selection has to be repeated in an independent way for every satellite image. The mathematical expression for $T*$ of the dry pixel with $\lambda E=0$ will be

$$T* = (R_n - G_0)/(\rho_a c_p u*) \qquad (\mathrm{K}) \tag{10}$$

With estimates of $(T*, T_s)$ for the dry and wet pixel, a and b from Eq. (9) are established for any image. This is the "self-calibration" of SEBAL that eliminates propagation of errors on the energy balance partitioning and the need for atmospheric correction of surface temperature and specific correction, by band, for short-wave reflection (Trezza 2002; Tasumi 2003). This attribute makes SEBAL relatively unique among the energy-balance based remote sensing methods. The values for $T*$ are, for instance, not dependent on T_s because a and b are adjusted to fit $T*$ extremes. The requirement of this procedure is that a dry area with $\lambda E \sim 0$ and a wet area with $H \sim 0$ are located on the image. The assumption is that hot and intense thermally emitting surfaces create higher vertical differences in air temperature ΔT than do cold surfaces with minor thermal emittance. Field research has demonstrated that the relationship between $\Delta T(T_s)$ is indeed linear (Wang et al. 1995; Franks and Beven 1999; Jacob et al. 2002).

The friction velocity $u*$ is determined from a single-layer wind-speed measurement that is obtained from any routine weather station

$$u* = (u_{z3}k)/[\ln(z_3/z_{0\mathrm{m}}) - \gamma_\mathrm{m}(z_3,L) + \gamma_\mathrm{m}(z_{0\mathrm{m}},L)] \qquad (\mathrm{m \cdot s^{-1}}) \tag{11}$$

where u_{z3} ($\mathrm{m \cdot s^{-1}}$)=the measured windspeed at height z_3; k (−)=von Karman's constant; $z_{0\mathrm{m}}$ (m)=the roughness length for momentum transport for any particular pixel; and γ_m (−)=the stability correction for momentum transport. The roughness length can be computed according to the vegetation index, vegetation height, or a combination of the two. The latter two approaches require a land use or crop classification with a look-up table for vegetation height. With pixel-based estimates of $u*$ and $T*$, sensible heat flux (H) can be computed according to Eq. (7) and, indirectly, the evaporative fraction using the formulation provided in Eq. (6). Because of limited spatial variability, it is preferable to consider a constant value for u_{z3} ($\mathrm{m \cdot s^{-1}}$) at a blending height having an elevation of 100 to 200 m. The wind speed at the blending height can be estimated from near-surface wind-speed measurements (Allen and Wright 1997). Using a logarithmic wind profile and a surface roughness for grass ($z_{0\mathrm{m}}=0.017$ m) or the prevalent vegetation upwind of a weather station, wind speed at, for instance 2.0 m, can be converted into wind speed at 100 m elevation.

Because the calculated value for H in Eq. (7) depends on the values for the stability functions in Eq. (9) and Eq. (11), an iterative solution is required. In the first instance, free convection is considered, and the correction terms ψ_h (Eq. (9)) and ψ_m (Eq. (11)) are ignored. Then, with first approximations of H available, mixed convection is applied, and buoyancy effects according to the Monin-Obukhov similarity hypothesis are incorporated using ψ_h and ψ_m (−). This requires an iterative loop between Eqs. (7), (9), and (11). After having established convergence on the H flux, ET is computed according to Eq. (4).

The inversion of the Penman-Monteith equation yields the possibility to reexpress ET as a bulk surface resistance to evaporation (r_s) on a 24 h timescale. The surface resistance expresses the biophysical-mathematical link between the state of conditions in the soil and the evapotranspiration into the atmosphere

$$\lambda E_{24} = (s_a R_{n24} + \rho_a c_p \Delta e/r_a)/[s_a + \gamma(1 + r_s/r_a)] \qquad (\mathrm{W \cdot m^{-2}}) \tag{12}$$

where s_a ($\mathrm{kPa \cdot K^{-1}}$)=the slope of the saturated vapour pressure; $\rho_a c_p$ ($\mathrm{J \cdot m^{-3}\,K^{-1}}$)=the air heat capacity; Δe (kPa)=the vapor pressure deficit; γ ($\mathrm{kPa \cdot K^{-1}}$)=the psychrometric constant and r_a ($\mathrm{s \cdot m^{-1}}$)=the aerodynamic resistance. The parameters s_a, Δe, and r_a are dominantly controlled by the overruling meteorological conditions. These parameters are all direct functions of meteorological conditions. The distributed r_s values so obtained are subsequently used to assess λE_{24} during days with overcast skies using Eq. (12) (Farah 2001). By accumulating λE_{24} for several days, time accumulated values of total ET can be obtained.

A refinement of the results can be obtained by making r_s between consecutive satellite images variable according to the condition of the soil-atmosphere system. The influence of atmospheric conditions is noticeable through the stomatal aperture response to ambient air temperatures (R_T), vapor pressure ($R_{\Delta e}$), and solar radiation (R_K), i.e. the Jarvis-Stewart model (Jarvis 1976; Stewart 1988)

$$r_s = r_s^{\min}/(\mathrm{LAI} R_T R_{\Delta e} R_K R_{\Delta}) \qquad (\mathrm{s} \cdot \mathrm{m}^{-1}) \tag{13}$$

in which LAI $(-)$ = the Leaf Area Index. The empirical R_x reduction functions have a value between 0 and 1. The influence of hydrology is expressed in the soil moisture-based resistance reduction factor R_Θ, which describes the change of resistance due to changes in soil moisture or soil water potential. More information on SEBAL can be found in the works by Bastiaanssen et al. (1998a), Farah and Bastiaanssen (2001), and Bastiaanssen et al. (2002).

Validation at Field Scale

Before discussing the potentials of SEBAL, an examination of its accuracy is needed. Several field methods exist to measure the evaporative fluxes and the partitioning of available radiant energy into sensible and latent heat fluxes. SEBAL has been tested against a variety of these *in situ* methods and environments described in Table 1. The table shows that SEBAL has been carefully inspected under a wide variety of conditions. Only a few validation experiments will be discerned hereafter.

The ET images generated by SEBAL for the lysimeters in Idaho show a progression of ET with time during years 1985 and 1989. Predicted ET compared well with ground measurements of ET made by lysimeter, with monthly differences for 1985 averaging $+/-16\%$ and 20% for 1989 but with seasonal differences of only 4% in 1985. In 1989, the difference between SEBAL (714 mm) and the lysimeter measurement (718 mm) was less than 1% for the sugar beet crop for the April 1–September 30 period (Allen et al. 2002). It appears that much of the error occurring on individual image acquisition dates was randomly distributed and tended to cancel.

In Sri Lanka, the sensible heat flux was independently measured with a scintillometer device (de Bruin et al. 1995) over mixed, humid tropical vegetation across a pathway of 1.94 km. The field instruments were installed in Horana. The Large Aperture Scintillometer (LAS) is an optical device used to monitor fluctuations in the refractive index of the turbulent atmosphere over a relatively large area. After combination of sensible heat flux with net radiation measurements, the actual ET was derived for approximately two National Oceanic and Atmospheric Administration (NOAA) satellite pixels (2,200 m). Hemakumara et al. (2003) found SEBAL errors to range between 4 to 32% on a 10-day basis. However, the errors were random, and the integration across time yielded monthly ET value that were only 3% different from the LAS measurements. This phenomena with reducing randomness by time integration was similar to that observed by the lysimeter studies in Idaho.

A test with a long-range scintillometer (XLAS) in The Netherlands revealed that the measured instantaneous sensible heat flux across a path of 9.8 km was 90 $\mathrm{W \cdot m^{-2}}$, while the SEBAL results estimated a value of 88 $\mathrm{W \cdot m^{-2}}$ for a line of 10 NOAA pixels (Kohsiek et al. 2002). The variability on the row of NOAA pixels ranged between 60 and 160 $\mathrm{W \cdot m^{-2}}$. The area consisted of productive grasslands with a shallow groundwater table.

Validation at Catchment Scale

The strength of a remote sensing technique is to describe the spatial variation of the ET fluxes at the regional scale. It is therefore interesting to validate the total volume of water evaporated from a large area. SEBAL results have been validated with catchment scale water balances that are "known" to the extent possible. In the Indus Basin, a water balance for an irrigated area of 3 million ha was compared against SEBAL. The mean SEBAL estimates of actual evapotranspiration for Rechna Doab averaged 940 mm/year from October 1993 to October 1994 (Bastiaanssen et al. 2002). The average annual ET (closure) for the water balance from June 1993 to June 1995 is 945 mm/year. Hence, the 5 mm difference (1%) between annual ET determined by SEBAL and the water balance is an excellent validation at the regional scale (Table 2).

Bastiaanssen and Chandrapala (2003) computed the water balance at the national scale for Sri Lanka for the period June 1999 to June 2000. The annual average rainfall over the island was 1,751 $\mathrm{mm \cdot year^{-1}}$. The annual average evaporation for SEBAL was 1,279 $\mathrm{mm \cdot year^{-1}}$. The rainfall surplus flows to the Indian Ocean was predicted to be 472 $\mathrm{mm \cdot year^{-1}}$ as an average for the whole island when storages are neglected. For two basins, river flows were measured and an independent calculation of ET could be established as a precipitation-runoff-storage change for all pixels that fall within these basin limits. The differences in ET between SEBAL and the water balance was found to be 1% and 11% for Kelani and Gin Ganga, respectively (Table 3).

In a similar study involving the hydrology of watersheds in Sri Lanka, Bastiaanssen and Bandara (2001) compared the estimated runoff from SEBAL-based ET maps with measured runoff of the Kirindi Oya river. Actual ET was estimated as the residual of the water balance (rainfall + irrigation-outflow), and appeared to be 1,295 mm. The SEBAL estimate was 1,356 $\mathrm{mm \cdot year^{-1}}$, which is a difference of 5%. This is a reasonable and true validation of water balances, because with the help of SEBAL, every term of the water balance can be estimated individually.

Mohamed et al. (2004) studied the vast swamps of the upper Nile basin in Sudan. Monthly evaporation and soil moisture storage maps were created by SEBAL for an area of 1,000 km $\cdot$ 1,000 km. The soil moisture data from SEBAL showed that the changes on an annual basis are small. This implies that all inflows (river inflow and precipitation) should balance with the outflow of the swamps (river outflow and evaporation). The evaporation for the 140,000 $\mathrm{km^2}$ vast area was only 4% different from the SEBAL value. Hence, the average deviation for large catchments in Pakistan, Sri Lanka, and Sudan appeared to be 4%.

Surface Energy Balance Algorithm for Land Application to District-Level Water Balances and Water Conservation

Selecting appropriate practices to conserve water and quantifying the volume of water conserved by those practices requires an accurate water balance. Typically, the largest and most important flow path in a water balance is *actual* evapotranspiration from irrigated lands. *Actual* evapotranspiration is difficult to determine accurately because most researchers calculate potential rather than actual evapotranspiration. Often *actual* evapotranspiration is assumed equal to the potential; however, some researchers (Irrigation Training and Research Center 2003) have begun estimating *actual* evapotranspiration as a fraction of the potential to account

Table 1. Validation of Surface Energy Balance Algorithm for Land (SEBAL)-Based Evapotranspiration (ET) Fluxes at Field Scale using Different Measurement Techniques

Field instrument	Country	Location and year	Landscape	Number of image dates compared	Source	Deviation instantaneous (%)	Deviation 1 to 10 days (%)
Drainage lysimeter	U.S.	Montpellier, Idaho, 1985	Irrigated native sedge forage	4	Morse et al. (2000), Allen et al. (2002)	NA	16
Weighing lysimeter	U.S.	Kimberly, Idaho, 1989	Irrigated sugar beet	12	Trezza (2002); Tasumi (2003); Allen et al. (2002)	NA	20
Bowen ratio	Egypt	Qattara Depression, 1986	Playas and desert surfaces	3	Bastiaanssen and Menenti (1990)	NA	2
Bowen ratio	Spain	Tomelloso, 1991	Rainfed crops	4	Pelgrum and Bastiaanssen (1996)	17	NA
Bowen ratio	Kenya	Naivasha, 1998	Savannah	10	Farah (2001)	NA	16
Bowen ratio	France	Alpilles, 1996	Alfalfa, wheat, sunflower	55	Jacob et al., (2002)	3[a] 23	NA NA
Eddy correlation	Spain	Tomelloso, 1991	Rainfed and irrigated crops	6	Pelgrum and Bastiaanssen (1996)	33	NA
Eddy correlation	China	Zhangye, 1991	Irrigated maize and deserts	2	Wang et al. (1995)	9	NA
Eddy correlation	Niger	Niamey, 1992	Savannah, tiger bush	3	Roerink (1995)	10	NA
Eddy correlation	The Netherlands	Cabauw Garderen, 1995	Forest, pastures	11	Bastiaanssen and Roozekrans (2003)	NA	30
Eddy correlation	New Mexico	Middle Rio Grande, 1999	Riparian vegetation	19	Unpublished	NA	5
Eddy correlation	Oklahoma	El Reno, 2001	Pastures	1	Schmugge et al. (2003)	5	NA
Scintillometer	Turkey	Gediz basin, 1998	Irrigated crops	4	Kite and Droogers (2000)	NA	16
Scintillometer	The Netherlands	Cabauw, 2002	Grassland	1	Kohsiek et al. (2002)	2[a]	NA
Scintillometer	Sri Lanka	Horana, 1999	Palm trees and rice	10	Hemakumara et al. (2003)	NA	16
Scintillometer	France	Alpilles, 1997	Sunflower, wheat, bare soil	1	Lagouarde et al. (2002)	1[a]	NA
Scintillometer	Morocco	Marrakech, 2003	Olives	17	van den Kroonenberg, A. (2003)	16 (NOAA) 11 (Landsat)	NA
Scintillometer	Botswana	Maun, 2001	Savannah	1	Timmermans et al. (2003)	1[a] 100	NA
Average						14%	15%

Note: NA=not applicable.

[a]Validation on sensible heat flux, not on ET flux.

for differences between the production agriculture environment and the pristine conditions under which potential evapotranspiration is estimated. Alternatively, a field-by-field water balance can estimate *actual* evapotranspiration if a schedule of irrigations, applied amounts and other factors, are known. Obviously, a field-by-field water balance is a laborious procedure, and often the necessary data on irrigations are not available. One of the main advantages of SEBAL for this type of application is the determi-

Table 2. Water Balance (Area of 30,000 km^2) based on Ground Measurements for Rechna Doab (Pakistan)

Measurements	1980–1995	June 1993–June 1994	June 1994–June 1995
Precipitation (mm)	435	315	420
Irrigation (mm)	605	558	560
River seepage (mm)	10	30	−5
Evapotranspiration (mm)	1,050	900	970
Residual term (mm)	0	3	5

Table 3. Annual Water Balance of Two Watersheds in Humid Tropics of Sri Lanka between June 1999 and June 2000

Measurements	Kelani Ganga	Gin Ganga
Area (km^2)	2,292	932
Measured annual rainfall (mm)	3,087	3,285
Measured runoff (mm)	1,823	1,850
Annual change storage based on SEBAL (mm)	−64	−71
Estimated ET as water balance residual (mm)	1,328	1,506
Annual SEBAL ET (mm)	1,310	1,333
ET difference (%)	1	11

Note: SEBAL=Surface Energy Balance Algorithm for Land; and ET=evapotranspiration.

nation of *actual* ET on a pixel-by-pixel spatial level.

The error in using potential evapotranspiration for *actual* evapotranspiration is revealed when the conveyance system water balance indicates that the irrigated lands cannot be transpiring at the potential rate. This situation was encountered in the water balance developed for a small irrigation district in the Yakima River basin in Washington State. A single SEBAL image was utilized to document the *actual* evapotranspiration from the irrigated lands during the peak period of crop water use. The *actual* evapotranspiration from this image was used to improve the accuracy of *actual* evapotranspiration estimates used for water balances depicting historical (used to represent without project) conditions and conditions under a potential conservation program (with project).

Fig. 1 shows an example of the ET rates in four windows of the Columbia River basin in Washington State. It demonstrates the significant spatial variability of ET for the different ecosystems present in the basin.

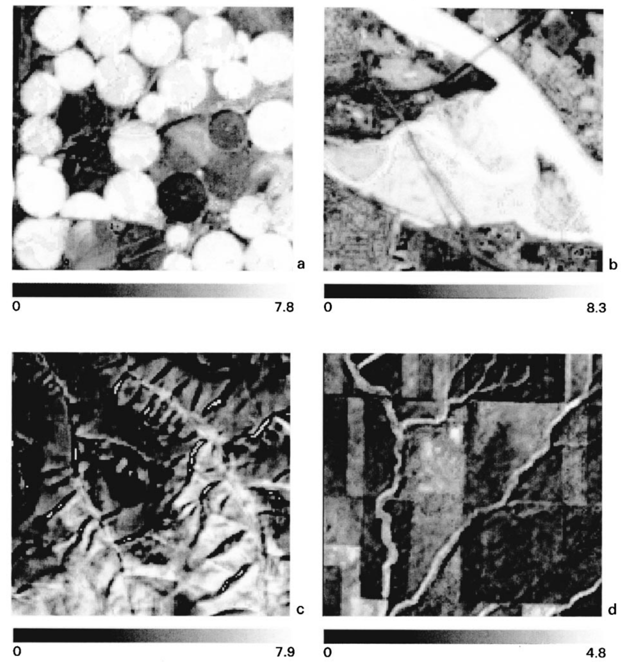

Fig. 1. Surface Energy Balance Algorithm for Land estimates of evapotranspiration (ET) (mm) for different ecosystems in the Columbia River basin (Washington State) on June 25, 2000. Part A consist of irrigated pivots (119°35′51″ W; 46°03′13″ N). Part B is riparian vegetation at the confluence of the Yakima and the Colombia (119°14′14″ W, 46°15′07″ N). Part C is the forests near Pendleton (118°53′30″ W, 45°20′39″ N), and Part D consists of rangeland (119°33′25″ W, 46°13′48″ N). The range in actual ET varies ($mm \cdot d^{-1}$ for every subimage and is specified underneath every panel.

Without-Project Crop Evapotranspiration using Surface Energy Balance Algorithm for Land

With a GIS tax parcel coverage of the area and parcel-specific crop records provided by the irrigation district, crop-specific actual ET statistics for the image data (July 25, 2000) were developed based on 30 m by 30 m pixels (Table 4). As expected, the crop with the greatest financial return, cherries, had the highest average actual ET at 6.9 mm/day. Cherries were followed in order by largest average actual ET by apple, alfalfa, nut, grass hay, and pasture. The average values are significantly lower than the maximum values, ranging from less than 50% for pasture to only 75% for cherries, indicating a significant amount of deficit irrigation. The maximum values can be viewed as achievable actual ET values given sufficient water supplies. The average actual ET value for each crop was assumed to represent average historical conditions within the district and was used to revise the without-project water balance.

With-Project Crop Evapotranspiration using Surface Energy Balance Algorithm for Land

Under the with-project condition, the existing open channel distribution system would be replaced with a pressurized pipe distribution system. Thus, the conveyance system losses will be negligible with the project. In this situation, an achievable *actual* evapotranspiration can be used together with on-farm efficiency to directly determine the district diversion requirements.

Table 4. Crop-Specific Actual Evapotranspiration (ET) Statistics for 30 m by 30 m Pixel $mm \cdot d^{-1}$

	Actual ET $mm \cdot d^{-1}$					
Crop	Minimum	Average	Standard Deviation	Maximum	10% exceedance	$Kc \times ET_o$ July
Cherry	0.0	6.9	1.8	9.1	8.6	8.4
Apple	3.0	6.4	1.0	8.6	7.6	9.1
Alfalfa	0.0	5.8	1.8	9.1	7.6	6.9
Nut	0.8	5.6	1.8	8.1	7.1	9.1
Grass hay	0.5	5.3	1.8	8.4	7.4	7.1
Pasture	0.0	4.6	2.3	9.4	7.1	7.1

An achievable *actual* evapotranspiration was based on a crop-specific *actual* ET rate exceeded by 10% of pixels in the SEBAL image and the with-project irrigated crop areas (Table 4). SEBAL provided information resulting in more accurate *actual* evapotranspiration values for both the with-project and with-out project water balances.

Conclusions

Hydrologic water balance and irrigation water management studies require accurate ET information under real circumstances, i.e., for heterogeneous terrain composed of various agroecosystems under erratic rainfall patterns, sparse canopies, and imperfectly managed irrigation and drainage systems. Ideally, ET information (1) has sufficient spatial detail to enable analysis at the field, project, and catchment levels; (2) covers large areas, such as entire river basins; and (3) considers nonpristine growing conditions. Remote sensing energy balance models such as SEBAL can produce ET estimates that meet these requirements.

The overall accuracy of ET from SEBAL for single-day events and for scales of the order of 100 ha is +/−15%. Space and time integration improves the accuracy. The seasonal differences are smaller (1 to 5%) due to reduction in the random error component (see results for Idaho, New Mexico, and Sri Lanka). Catchment-scale studies in Pakistan, Sri Lanka, and Sudan reveal an overall deviation of 4% on an annual basis. It is unlikely that these accuracies will ever be improved much further in the short-term, because most regional scale hydrological databases (of precipitation, stream flow, weather, etc.) lack sufficient accuracy. These accuracies are in agreement with an earlier review of ET errors originating from SEBAL (Bastiaanssen et al. 1998b).

The extensive testing of SEBAL across a variety of climates and ecosystem during the past 10 years shows that the technique has passed the test; SEBAL can be applied and implemented for solving water resources and irrigation problems. It is anticipated that SEBAL can help in establishing (1) the relationship between land use and water use for river basin planning; (2) studying impact of water conservation projects on real water savings; (3) irrigation performance; (4) environmental impact assessment due to groundwater extractions; (5) assessing the effect of water transfer design; (6) water-rights compliance; (7) hydrological modelling; (8) monitoring degradation of native vegetation systems; (9) forest vitality; and (10) assessing crop water productivity, to name a few applications.

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Appendix I. Surface Energy Balance Algorithm for Land Studies Carried out by International Research Groups, Universities, and Consultants During 1992–2003

Continent	Country	Research	Application
Europe	The Netherlands	√	√
	Spain	√	√
	Portugal	√	
	Italy	√	
	France	√	
	Belgium	√	
Asia	Turkey	√	√
	Iran	√	
	Uzbekistan	√	√
	Kirgistan		√
	Tajikistan		√
	Pakistan	√	
	India	√	
	Sri Lanka	√	√
	China	√	√
	Philippines	√	
Africa	Egypt	√	√
	Sudan	√	
	Kenya	√	
	Niger	√	
	Zimbabwe	√	
	Botswana	√	
	South Africa		√
	Morocco	√	
	Zambia	√	
Americas	Idaho	√	√
	New Mexico	√	
	Oklahoma	√	
	Florida		√
	Washington		√
	California		√
	Mexico		√
	Panama		√
	Brazil		√
	Argentina	√	
Total		26	17

References

Allen, R. G. (2000). "Using the FAO-56 dual crop coefficient method over an irrigated region as part of an evapotranspiration intercomparison study." *J. Hydrol.*, 229, 27–41.

Allen, R. G., et al. (2002). "Evapotranspiration from a satellite-BASED surface energy balance for the Snake Plain Aquifer in Idaho." *Proc. USCID Conference*, USCID, Denver.

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). "Crop evapotranspiration, guidelines for computing crop water requirements." *FAO Irrigation and Drainage Paper 56*, Food and Agriculture Organization of the United Nations (FAO), Rome.

Allen, R. G., Pruitt, W. O., and Jensen, M. E. (1991). "Environmental Requirements of Lysimeters." *Proc., Lysimeters for Evapotranspiration and Environmental Measurements*, ASCE, New York, 170–181.

Allen, R. G., and Wright, J. L. (1997). "Translating wind measurements from weather stations to agricultural crops." *J. Hydrologic Eng.*, 2(1),

26–35.
Bastiaanssen, W. G. M., and Bandara, K. M. P. S. (2001). "Evaporative depletion assessments for irrigated watersheds in Sri Lanka." *Irrig. Sci.*, 21, 1–15.
Bastiaanssen, W. G. M., and Bos, M. G. (1999). "Irrigation performance indicators based on remotely sensed data: a review of literature." *Irrig. Drain. Syst.*, 13, 291–311.
Bastiaanssen, W. G. M., and Chandrapala, L. (2003). "Water balance variability across Sri Lanka for assessing agricultural and environmental water use." *Agric. Water Manage.*, 58(2), 171–192.
Bastiaanssen, W. G. M., and Menenti, M. (1990). "Mapping groundwater losses in the western Desert of Egypt with satellite measurements of surface reflectance and surface temperature." *Water Management and Remote Sensing*, J. C. Hooghart, ed., TNO, The Hague, The Netherlands, 1–90.
Bastiaanssen, W. G. M., Menenti, M., Feddes, R. A., and Holtslag, A. A. M. (1998a). "A remote sensing surface energy balance algorithm for Land (SEBAL), Part 1: Formulation." *J. Hydrol.*, 212-213, 198–212.
Bastiaanssen, W. G. M., Molden, D. J., and Makin, I. W. (2000). "Remote sensing for irrigated agriculture: Examples from research of possible applications." *Agric. Water Manage.*, 46(2), 137–155.
Bastiaanssen, W. G. M., Pelgrum, H., Wang, J., Ma, Y., Moreno, J., Roerink, G. J., and van der Wal, T. (1998b). "The surface energy balance algorithm for land (SEBAL), Part 2: Validation." *J. Hydrol.*, 212-213, 213–229.
Bastiaanssen, W. G. M., Roest, C. W. J., Pelgrum, H., and Abdel Khalek, M. A. (1992). "Monitoring of the irrigation performance on the basis of actual evapotranspiration: Comparison of satellite data and simulation model results," *Advances in planning, design and management of irrigation systems as related to substainable land use*, Center for Irrigation Engineering and ECOWARM, Leuven, Belgium, 473–483.
Bastiaanssen, W. G. M., and Roozekrans, H. (2003). "Vlakdekkende actuele verdamping van Nederland operationeel beschikbaar." *Stromingen*, 9(4), 5–19 (in Dutch).
Bastiaanssen, W. G. M., Ud-din-Ahmed, M., and Chemin, Y. (2002). "Satellite surveillance of water use across the Indus Basin." *Water Resour. Res.*, 38(12), 1273–1282.
Beljaars, A. C. M., and Holtslag, A. A. M. (1991). "On flux parameterization over land surfaces for atmospheric models." *J. Appl. Meteorol.*, 30, 327–341.
Bos, M. G., Murray-Rust, D. H., Merrey, D. J., Johnson, H. G., and Snellen, W. B. (1994). "Methodologies for assessing performance of irrigation and drainage management." *Irrig. Drain. Syst.*, 7, 231–261.
Bruin, de, H. A. R., and Stricker, J. N. M. (2000). "Evaporation of grass under non-restricted soil moisture conditions." *Hydrol. Sci. J.*, 45(3), 391–406.
Bruin, H. A. R., van den Hurk, B. J. J. M., and Kohsiek, W. (1995). "The scintillation method tested over a dry vineyard area." *Boundary-Layer Meteorol.*, 76, 25–40.
Brutsaert, W. (1982). *Evaporation into the atmosphere, theory, history and applications*, Reidel, Dordrecht, The Netherlands.
Brutsaert, W., Hsu, A. Y., and Schmugge, T. J. (1993). "Parameterization of surface heat fluxes above forests with satellite thermal sensing and boundary layer soundings." *J. Appl. Meteorol.*, 32(5), 909–917.
Brutsaert, W., and Sugita, M. (1992). "Application of self-preservation in the diurnal evolution of the surface energy balance budget to determine daily evaporation." *J. Geophys. Res.*, 97(D17), 18377–18382.
Carlson, T. M., Taconet, O., Vidal, A., Gillies, R. R., Olios, A., and Humes, K. (1995). "An overview of the workshop on thermal remote sensing held at La Londe les Maures, France." *Agric. Forest Meteorol.*, 77, 141–151.
Chehbouni, A., Lo Seen, D., Njoku, E. G., Lhomme, J. P., Monteney, B., and Kerr, Y. H. (1997). "Estimation of sensible heat flux over sparsely vegetated surfaces." *J. Hydrol.*, 188-189, 855–868.
Coureault, D., Seguin, B., and Olioso, A. (2004). "Review about estimation of evapotranspiration from remote sensing data: From empirical to numerical modeling approach." *Irrig. Drain. Syst.*, 19 (in press).
Crago, R. D. (1996). "Comparison of the evaporative fraction and the Priestley-Taylor α for parameterizing daytime evaporation." *Water Resour. Res.*, 32(5), 1403–1409.
Doorenbos, J., and Pruitt, W. O. (1977). "Crop water requirements." *Irrigation and Drainage Paper No. 24*, FAO, Rome.
Droogers, P. (2000). "Estimating actual evapotranspiration using a detailed agro-hydrological model." *J. Hydrol.*, 229(1–2), 50–58.
Farah, H. O. (2001). "Estimation of regional evaporation under all sky conditions with satellite and routine weather data." PhD thesis, Wageningen University, The Netherlands.
Farah, H. O., and Bastiaanssen, W. G. M. (2001). "Spatial variations of surface parameters and related evaporation in the Lake Naivasha Basin estimated from remote sensing measurements." *Hydrol. Process.*, 15(9), 1585–1607.
Franks, S. W., and Beven, K. J. (1997). "Estimation of evapotranspiration at the landscape scale: A fuzzy disaggregation approach." *Water Resour. Res.*, 33(12), 2929–2938.
Franks, S. W., and Beven, K. J. (1999). "Conditioning a multiple-patch SVAT model using uncertain time-space estimates of latent heat flux as inferred from remotely sensed data." *Water Resour. Res.*, 35(9), 2751–2761.
Hemakumara, H. M., Chandrapala, L., and Moene, A. (2003). "Evapotranspiration fluxes over mixed vegetation areas measured from large aperture scintillometer." *Agric. Water Manage.*, 58, 109–122.
Irrigation Training and Research Center (ITRC). (2003). ⟨http://www.itrc.org/ETWeb/WBandISHomePage.htm⟩.
Jacob, F., Olioso, A., Gu, X. F., Su, Z., and Seguin, B. (2002). "Mapping surface fluxes using airborne visible, near infrared, thermal infrared remote sensing data and a spatialized surface energy balance model." *Agronomie*, 22, 669–680.
Jarvis, P. G. (1976). "The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field." *Philos. Trans. R. Soc. London, Ser. B*, B273, 593–610.
Jensen, M. E., Burman, R. D., and Allen, R. G. (1990). "Evapotranspiration and irrigation water requirements, ASCE manuals and reports on engineering practice," No. 70, ASCE, New York.
Kalma, J. D., and Jupp, D. L. B. (1990). "Estimating evaporation from pasture using infrared thermometry: Evaluation of a one-layer resistance model." *Agric. Forest Meteorol.*, 51, 223–246.
Kijne, J., Barker, R., and Molden, D. (2003). "Water productivity in agriculture: Limits and opportunities for improvement." CABI Publishing, Wallingford, U.K.
Kite, G. W., and Droogers, P. (2000). "Comparing evapotranspiration estimates from satellites, hydrological models and field data." *J. Hydrol.*, 229(1-2), 3–18.
Kohsiek, W., Meijninger, W., and de Bruin, H. A. R. (2002). "Long range scintillometry." *Proc., Int. Symp. on Boundary Layer Physics*.
Lagouarde, J. P., et al. (2002). "Spatialization of sensible heat flux over a heterogeneous landscape." *Agronomie*, 22, 627–633.
Menenti, M. (2000). "Irrigation and drainage." Chapter 17, Remote sensing in hydrology and water management, Springer, Berlin, 377–400.
Mohamed, Y., Bastiaanssen, W. G. M., and Savenije, H. H. G. (2004). "Spatial variability of evaporation and moisture storage in the swamps of the upper Nile studied by remote sensing techniques." *J. Hydrol.*, 277, 116–124.
Morse, A., Tasumi, M., Allen, R. G., and Kramber, W. J. (2000). "Application of the SEBAL methodology for estimating consumptive use of water and streamflow depletion in the Bear River basin of Idaho through remote sensing." *Final Rep., Phase I,* Submitted to Raytheon Systems, Earth Observation System Data and Information System Project, by Idaho Dept. of Water Resources and Univ. of Idaho.
Murray-Rust, D. H., and Snellen, W. B. (1993). "Irrigation system performance assessment and diagnosis." International Water Management Institute, Colombo, Sri Lanka.
Nicols, W. E., and Cuenca, R. H. (1993). "Evaluation of the evaporative fraction for parameterization of the surface energy balance." *Water Resour. Res.*, 29(11), 3681–3690.
Pelgrum, H., and Bastiaanssen, W. G. M. (1996). "An intercomparison of techniques to determine the area-averaged latent heat flux from individual in situ observations: A remote sensing approach using EFEDA

data." *Water Resour. Res.*, 32(9), 2775–2786.

Perry, C. J. (1999). "The IWMI water resources paradigm—Definitions and implications." *Agric. Water Manage.*, 40, 45–50.

Roerink, G. J. (1995). "SEBAL estimates of the areal patterns of sensible and latent heat fluxes over the HAPEX-Sahel grid, a case study on 18 September 1992." *DLO-Staring Centre Interne Mededeling 364*, Alterra, Wageningen.

Schmugge, T. J., Jacob, F., French, A., and Kustas, W. P. (2003). "Surface flux estimates with ASTER thermal infrared data." *ASTER Workshop*.

Shuttleworth, W. J., Gurney, R. J., Hsu, A. Y., and Ormsby, J. P. (1989). "FIFE: The variation in energy partioning at surface flux sites, remote sensing and large scale global processes." *Proc., Red Book 186*, International Association of Hydrological Sciences (IAHS), Delft, The Netherlands, 67–74.

Simunek, J., Vogel, T., and van Genuchten, M. Th. (1994). "The SWMS_2D code for simulating water flow and solute transport in two-dimensional variably saturated media." Version 1.21., *Research Rep. No. 132*, U.S. Salinity Laboratory, USDA, ARS, Riverside, Calif.

Stewart, J. B. (1988). "Modelling surface conductance of pine forest." *Agric. Forest Meteorol.*, 43, 19–35.

Stewart, J. B., Kustas, W. P., Humes, K. S., Nichols, W. D., Moran, M. S., and de Bruin, H. A. R. (1994). "Sensible heat flux-radiometric surface temperature relationship from 8 semi-arid areas." *J. Appl. Meteorol.*, 33, 1110–1117.

Stewart, J. B., Watts, C. J., Rodriguez, J. C., De Bruin, H. A. R., van den Berg, A. R., and Garatuza-Payan, J. (1999). "Use of satellite data to estimate radiation and evaporation for northwest Mexico." *Agric. Water Manage.*, 38, 181–193.

Sugita, M., and Brutsaert, W. (1990). "Regional surface fluxes from remotely sensed skin temperature and lower boundary layer measurements." *Water Resour. Res.*, 26(12), 2937–2944.

Tasumi, M. (2003). "Progress in operational estimation of regional evapotranspiration using satellite imagery." PhD thesis, Dept. Biological and Agricultural Engineering, Univ. Idaho.

Timmermans, W. J., Gieske, A. S., Kustas, W. P., Wolski, P., Arneth, A., and Parodi, G. N. (2003). "Determination of water and heat fluxes with MODIS imagery—Maun, Botswana." *Proc., Int. Symp. SPIE USE V 16 5232-55*, SPIE, Bellingham, Wash.

Trezza, R. (2002). "Evapotranspiration using a satellite-based surface energy balance with standardized ground control." PhD thesis, Dept., Biological and Irrigation Engineering, Utah State Univ.

Troufleau, D., Lhomme, J. P., Monteney, B., and Vidal, A. (1997). "Sensible heat flux and radiometric surface temperature over sparse Sahelian vegetation. I. An experimental analysis of the kB^{-1} parameter." *J. Hydrol.*, 188–189, 815–838.

Twine, T. E., et al. (2000). "Correcting eddy covariance flux underestimates over a grassland." *Agric. Forest Meteorol.*, 103, 279–300.

van den Kroonenberg, A. (2003). "Surface flux estimates over an olive yard: SEBAL method applied to NOAA-KLM and Landsat-7," MS thesis, Wageningen Univ., Dept. of Meterology.

Kustas, W. P., Perry, E. M., Doraiswamy, P. C., and Moran, M. S. (1994). "Using satellite remote sensing to extrapolate evapotranspiration estimates in time and space over a semiarid rangeland basin." *Remote Sens. Environ.*, 49, 275–286.

Wang, J., Ma, Y., Menenti, M., Bastiaanssen, W. G. M., and Mitsuta, Y. (1995). "The scaling up of land surface processes over a heterogeneous landscape with satellite observations." *J. Meteorol. Soc. Jpn.*, 73(6), 1235–1244.

Wright, J. L. (1982). "New evapotranspiration crop coefficients." *J. Irrig. Drain. Div.*, 108(1), 57–74.

Wright, J. L., and Jensen, M. E. (1972). "Peak water requirements of crops in Southern Idaho." *J. Irrig. Drain. Div.*, 96(1), 193–201.