CIVE 519 - Irrigation Water Management

FALL 2024

Lecture 20

Remote Sensing of ET: SEBAL Algorithm Principles

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Remote sensing models for ET

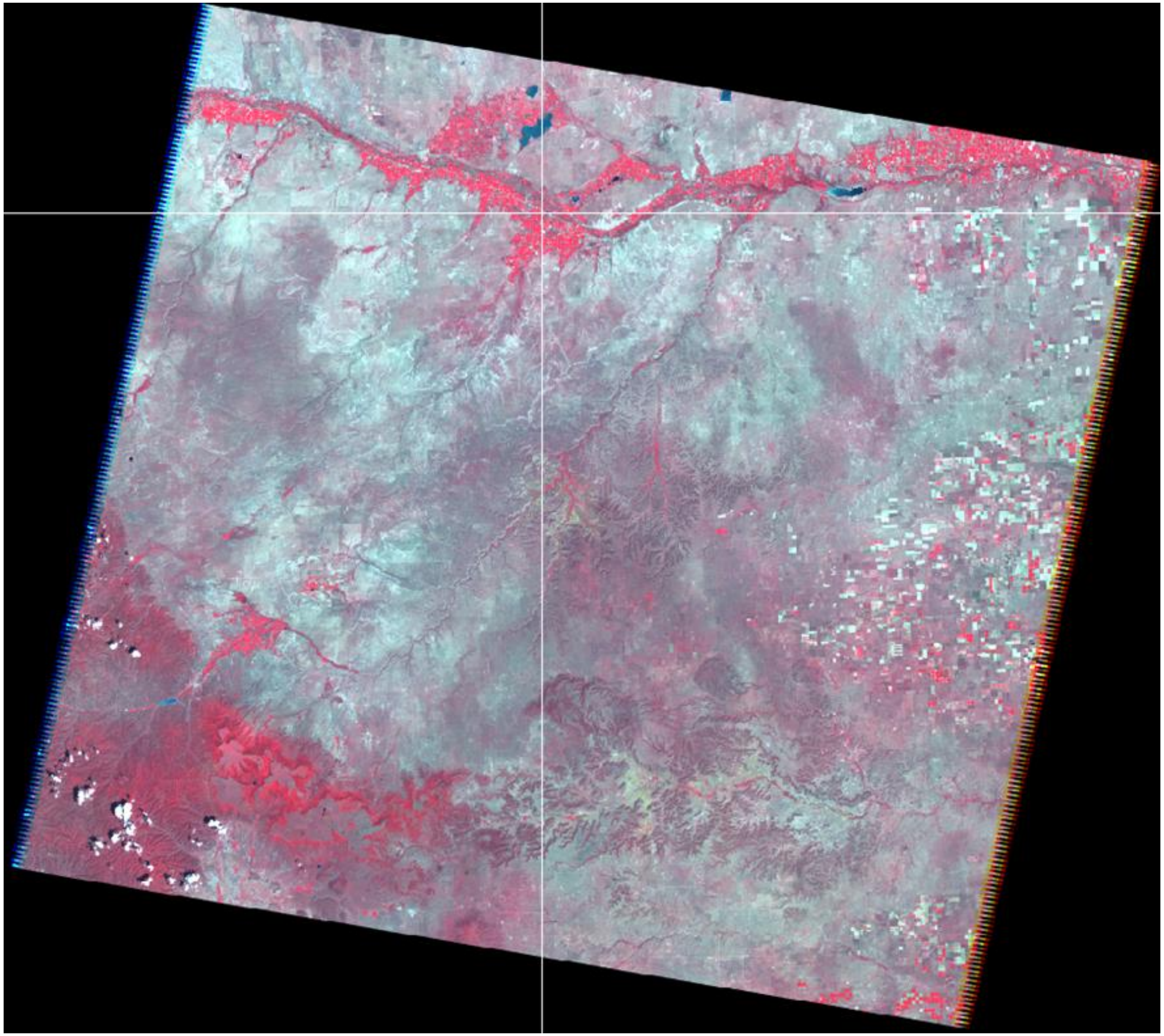
- These use the energy balance equation to estimate ET.

$$\mathbf{R_n - LE - G - H = 0}$$

- Modeling R_n, G and H, then determining **LE** as a residual: $\mathbf{(R_n - G) - H = LE}$

- Several models have been developed; SEBAL, SEBAL-A, METRIC, ReSET, SAT, ALARM, S-SEBI, SSEBop, ALEXI, etc.

Landsat 8 scene



SEBAL

Surface Energy Balance Algorithm for Land

SEBAL

- Developed by Dr. Wim Bastiaanssen, Wageningen, The Netherlands
- It combines Remotely sensed data and ground-based data (wind speed, solar radiation)
- Output would be a map of ETa

Satellite images that can be used in SEBAL

- NASA- Landsat 5, 7, 8, 9, (30 m VIS, 100-120 m TIR), swath ~185 km

- NOAA-AVHRR (advanced very high resolution radiometer), (1 km, daily), swath 2399 km

- NASA-MODIS (moderate resolution imaging spectroradiometer), 500 m VIS & 1000 m TIR, daily, swath 2330 km.

- NASA-ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), 15 m VIS, 90 m TIR, 8 days, 60 km swath.

SEBAL processing steps

1. Digital Number (DN) to Radiance
2. Spectral Reflectance
3. Surface albedo at the top of atmosphere
4. Surface albedo at the bottom of the atmosphere
5. Vegetation indices (NDVI, LAI)
6. Thermal infra-red surface emissivity
7. Radiometric surface temperature (T_s)
8. Net radiation (R_n)
9. Soil Heat Flux (G)
10. Surface roughness for momentum transfer (Zom)
11. Initial (neutral condition) friction velocity (u_*) and r_{ah}

SEBAL processing steps (cont.)

12. Initial (neutral cond.) sensible heat flux
13. First stability correction (MOST) u_* and r_{ah}
14. Stability corrected H (first correction)
15. Stability correction repeated several times
20. Instantaneous LE (ET)
21. Evaporative Fraction (EF)
22. Daily Net radiation (Rn_{24})
23. Daily ET (ET_{24})

Modeling of heat fluxes

LE = latent heat flux = Rn – G – H

- Net Radiation (R_n) = Rn_shortwave + Rn_longwave

$$R_n = ((1 - \alpha)\, R_s) + (\varepsilon_a \sigma T_a^{\,4} - \varepsilon_s \sigma T_s^{\,4})$$

- Soil Heat Flux (G)

$$G = (T_s/\alpha)\,(0.0038\alpha + 0.0074\alpha^2)\,(1 - 0.98 NDVI^4)\, R_n$$

- Sensible Heat Flux (H) original definition:

$$H = \rho_a C_{pa}\,(T_o - T_a)/r_{ah}$$

T_o = aerodynamic temperature, °C

- However SEBAL instead uses the dT function in the place of (T_o – T_a) due to difficulty in measuring/estimating T_o

$$H = \rho_a C_{pa}\, dT\, /\, r_{ah}$$

Modeling of heat fluxes (cont.)

- LE is therefore obtained as a residual:

$$LE = R_n - G - H$$

- To extrapolate from instantaneous to daily ET, evaporative fraction (EF) is determined and then assumed to be constant throughout the day

$$EF = \frac{LE}{Rn - G}$$

$$ET_{24} = \frac{86{,}400 \times EF \times (Rn_{24} - G_{24})}{\lambda}$$

Where λ is the latent heat of vaporization to convert to mm/d

Satellite Bands

Table 1 Repeat cycle, spectral and spatial resolution of spectral bands on ASTER, Landsat 5, and MODIS sensors

Satellite	Repeat cycle	Spectral band	Wavelength (μm)	Spatial resolution (m)
ASTER	16 days (nadir)	1	0.52–0.60 (green)	15
		2	0.63–0.69 (red)	
		3	0.76–0.86 (NIR)	
		5	1.600–1.700 (SWIR)	30
		6	2.145–2.185 (SWIR)	
		7	2.185–2.225 (SWIR)	
		8	2.235–2.285 (SWIR)	
		9	2.295–2.365 (SWIR)	
		10	2.360–2.430 (SWIR)	
		11	8.125–8.475 (TIR)	90
		12	8.475–8.825 (TIR)	
		13	8.925–9.275 (TIR)	
		14	10.25–10.95 (TIR)	
		15	10.95–11.65 (TIR)	
TM	16 days	1	0.45–0.52 (blue)	30
		2	0.52–0.60 (green)	
		3	0.63–0.69 (red)	
		4	0.76–0.90 (NIR)	
		5	1.55–1.75 (SWIR)	
		7	2.08–2.35 (SWIR)	
		6	10.4–12.5 (TIR)	120
MODIS	Daily	1	0.62–0.67 (red)	250
		2	0.841–0.876 (NIR)	
		3	0.459–0.479 (blue)	500
		4	0.545–0.565 (green)	
		5	1.230–1.250 (SWIR)	
		6	1.628–1.652 (SWIR)	
		7	2.105–2.155 (SWIR)	
		31	10.780–11.280 (TIR)	1,000
		32	11.770–12.270 (TIR)	

NIR Near infrared, *SWIR* shortwave infrared, *TIR* thermal infrared

Satellite Bands

Landsat-7 ETM+ Bands (µm)			Landsat-8 OLI and *TIRS* Bands (µm)		
			30 m Coastal/Aerosol	0.435 - 0.451	Band 1
Band 1	30 m Blue	0.441 - 0.514	30 m Blue	0.452 - 0.512	Band 2
Band 2	30 m Green	0.519 - 0.601	30 m Green	0.533 - 0.590	Band 3
Band 3	30 m Red	0.631 - 0.692	30 m Red	0.636 - 0.673	Band 4
Band 4	30 m NIR	0.772 - 0.898	30 m NIR	0.851 - 0.879	Band 5
Band 5	30 m SWIR-1	1.547 - 1.749	30 m SWIR-1	1.566 - 1.651	Band 6
Band 6	60 m TIR	10.31 - 12.36	*100 m TIR-1*	*10.60 – 11.19*	Band 10
			100 m TIR-2	*11.50 – 12.51*	Band 11
Band 7	30 m SWIR-2	2.064 - 2.345	30 m SWIR-2	2.107 - 2.294	Band 7
Band 8	15 m Pan	0.515 - 0.896	15 m Pan	0.503 - 0.676	Band 8
			30 m Cirrus	1.363 - 1.384	Band 9

SEBAL Implementation: Step 1

Digital Number (DN) to Radiance conversion.

For Landsat 5:

$$L_\lambda = \left(\frac{LMAX - LMIN}{255}\right) \text{X } DN + LMIN$$

L_λ= spectral radiance at sensor's aperture for each band

LMIN= spectral at-sensor radiance scaled to minimum

LMAX = spectral at-sensor radiance scaled to maximum

DN = digital number (raw image pixel values)

Calibration coefficients for Landsat 7

Table 4
ETM+ spectral range, post-calibration dynamic ranges, and mean exoatmospheric solar irradiance ($ESUN_\lambda$).

L7 ETM+ Sensor ($Q_{cal\,min}=1$ and $Q_{cal\,max}=255$)							
Band	Spectral range	Center wavelength	$LMIN_\lambda$	$LMAX_\lambda$	$G_{rescale}$	$B_{rescale}$	$ESUN_\lambda$
Units	μm		W/(m² sr μm)		(W/m² sr μm)/DN	W/(m² sr μm)	W/(m² μm)
Low gain (LPGS)							
1	0.452–0.514	0.483	−6.2	293.7	1.180709	−7.38	1997
2	0.519–0.601	0.560	−6.4	300.9	1.209843	−7.61	1812
3	0.631–0.692	0.662	−5.0	234.4	0.942520	−5.94	1533
4	0.772–0.898	0.835	−5.1	241.1	0.969291	−6.07	1039
5	1.547–1.748	1.648	−1.0	47.57	0.191220	−1.19	230.8
6	10.31–12.36	11.335	0.0	17.04	0.067087	−0.07	N/A
7	2.065–2.346	2.206	−0.35	16.54	0.066496	−0.42	84.90
PAN	0.515–0.896	0.706	−4.7	243.1	0.975591	−5.68	1362
High Gain (LPGS)							
1	0.452–0.514	0.483	−6.2	191.6	0.778740	−6.98	1997
2	0.519–0.601	0.560	−6.4	196.5	0.798819	−7.20	1812
3	0.631–0.692	0.662	−5.0	152.9	0.621654	−5.62	1533
4	0.772–0.898	0.835	−5.1	157.4	0.639764	−5.74	1039
5	1.547–1.748	1.648	−1.0	31.06	0.126220	−1.13	230.8
6	10.31–12.36	11.335	3.2	12.65	0.037205	3.16	N/A
7	2.065–2.346	2.206	−0.35	10.80	0.043898	−0.39	84.90
PAN	0.515–0.896	0.706	−4.7	158.3	0.641732	−5.34	1362

Section 5 Conversion of DNs to Physical Units

5.1 OLI and TIRS at Sensor Spectral Radiance

Images are processed in units of absolute radiance using 32-bit floating-point calculations. These values are then converted to 16-bit integer values in the finished Level 1 product. These values can then be converted to spectral radiance using the radiance scaling factors provided in the metadata file:

$$L_\lambda = M_L * Q_{cal} + A_L$$

where:

L_λ = Spectral radiance ($W/(m^2 * sr * \mu m)$)
M_L = Radiance multiplicative scaling factor for the band (RADIANCE_MULT_BAND_n from the metadata)
A_L = Radiance additive scaling factor for the band (RADIANCE_ADD_BAND_n from the metadata).
Q_{cal} = L1 pixel value in DN

5.2 OLI Top of Atmosphere Reflectance

Similar to the conversion to radiance, the 16-bit integer values in the L1 product can also be converted to TOA reflectance. The following equation is used to convert Level 1 DN values to TOA reflectance:

$$\rho\lambda' = M_\rho * Q_{cal} + A_\rho$$

where:

ρ_λ' = TOA Planetary Spectral Reflectance, without correction for solar angle. (Unitless)
M_ρ = Reflectance multiplicative scaling factor for the band (REFLECTANCEW_MULT_BAND_n from the metadata).
A_ρ = Reflectance additive scaling factor for the band (REFLECTANCE_ADD_BAND_N from the metadata).
Q_{cal} = L1 pixel value in DN

Note that ρ_λ' is not true TOA Reflectance, because it does not contain a correction for the solar elevation angle. This correction factor is left out of the L1 scaling at the users' request; some users are content with the scene-center solar elevation angle in the metadata, while others prefer to calculate their own per-pixel solar elevation angle across the entire scene. Once a solar elevation angle is chosen, the conversion to true TOA Reflectance is as follows:

$$\rho_\lambda = \frac{\rho_\lambda'}{\sin(\theta)}$$

$$\rho_\lambda = \frac{\rho_\lambda'}{\sin(\theta)}$$

where:

ρ_λ	=	TOA Planetary Reflectance (Unitless)
θ	=	Solar Elevation Angle (from the metadata, or calculated)

5.3 TIRS Top of Atmosphere Brightness Temperature

TIRS data can also be converted from spectral radiance (as described above) to brightness temperature, which is the effective temperature viewed by the satellite under an assumption of unity emissivity. The conversion formula is as follows:

$$T = \frac{K2}{\ln\left(\frac{K1}{L_\lambda} + 1\right)}$$

K1_CONSTANT_BAND_10 = 774.89
K1_CONSTANT_BAND_11 = 480.89
K2_CONSTANT_BAND_10 = 1321.08
K2_CONSTANT_BAND_11 = 1201.14

where:

T = TOA Brightness Temperature, in Kelvin.
L_λ = Spectral radiance (Watts/(m^2 * sr * μm))
K1 = Thermal conversion constant for the band (K1_CONSTANT_BAND_n from the metadata)
K2 = Thermal conversion constant for the band (K2_CONSTANT_BAND_n from the metadata)

GROUP = RADIOMETRIC_RESCALING
RADIANCE_MULT_BAND_1 = 1.2220E-02
RADIANCE_MULT_BAND_2 = 1.2514E-02
RADIANCE_MULT_BAND_3 = 1.1531E-02
RADIANCE_MULT_BAND_4 = 9.7239E-03
RADIANCE_MULT_BAND_5 = 5.9506E-03
RADIANCE_MULT_BAND_6 = 1.4799E-03
RADIANCE_MULT_BAND_7 = 4.9879E-04
RADIANCE_MULT_BAND_8 = 1.1005E-02
RADIANCE_MULT_BAND_9 = 2.3256E-03
RADIANCE_MULT_BAND_10 = 3.3420E-04
RADIANCE_MULT_BAND_11 = 3.3420E-04
RADIANCE_ADD_BAND_1 = -61.10214
RADIANCE_ADD_BAND_2 = -62.56934
RADIANCE_ADD_BAND_3 = -57.65711
RADIANCE_ADD_BAND_4 = -48.61972
RADIANCE_ADD_BAND_5 = -29.75285
RADIANCE_ADD_BAND_6 = -7.39926
RADIANCE_ADD_BAND_7 = -2.49395
RADIANCE_ADD_BAND_8 = -55.02415
RADIANCE_ADD_BAND_9 = -11.62809
RADIANCE_ADD_BAND_10 = 0.10000
RADIANCE_ADD_BAND_11 = 0.10000

REFLECTANCE_MULT_BAND_1 = 2.0000E-05
REFLECTANCE_MULT_BAND_2 = 2.0000E-05
REFLECTANCE_MULT_BAND_3 = 2.0000E-05
REFLECTANCE_MULT_BAND_4 = 2.0000E-05
REFLECTANCE_MULT_BAND_5 = 2.0000E-05
REFLECTANCE_MULT_BAND_6 = 2.0000E-05
REFLECTANCE_MULT_BAND_7 = 2.0000E-05
REFLECTANCE_MULT_BAND_8 = 2.0000E-05 -
95 - LSDS-1574 Version 2.0

REFLECTANCE_MULT_BAND_9 = 2.0000E-05
REFLECTANCE_ADD_BAND_1 = -0.100000
REFLECTANCE_ADD_BAND_2 = -0.100000
REFLECTANCE_ADD_BAND_3 = -0.100000
REFLECTANCE_ADD_BAND_4 = -0.100000
REFLECTANCE_ADD_BAND_5 = -0.100000
REFLECTANCE_ADD_BAND_6 = -0.100000
REFLECTANCE_ADD_BAND_7 = -0.100000
REFLECTANCE_ADD_BAND_8 = -0.100000
REFLECTANCE_ADD_BAND_9 = -0.100000
END_GROUP = RADIOMETRIC_RESCALING

SEBAL Step 2

Spectral Reflectance computation for a given band (***Landsat 5 and 7***):

$$\rho_\lambda = \frac{\pi \times L_\lambda}{ESUN_\lambda \times COS\Theta_s \times d_r}$$

d_r is the inversed squared relative earth-sun distance, $d_r = \frac{1}{d^2}$

$$d_r = 1 + 0.033\cos\left(DOY\frac{2\pi}{365}\right)$$

θ_s = is the solar incident (zenith) angle (90°minus the sun elevation angle)

$ESUN_\lambda$ = the mean exoatmospheric irradiance for a band, $Wm^{-2}\ m^{-1}$

d_r = the earth-sun distance in astronomical units

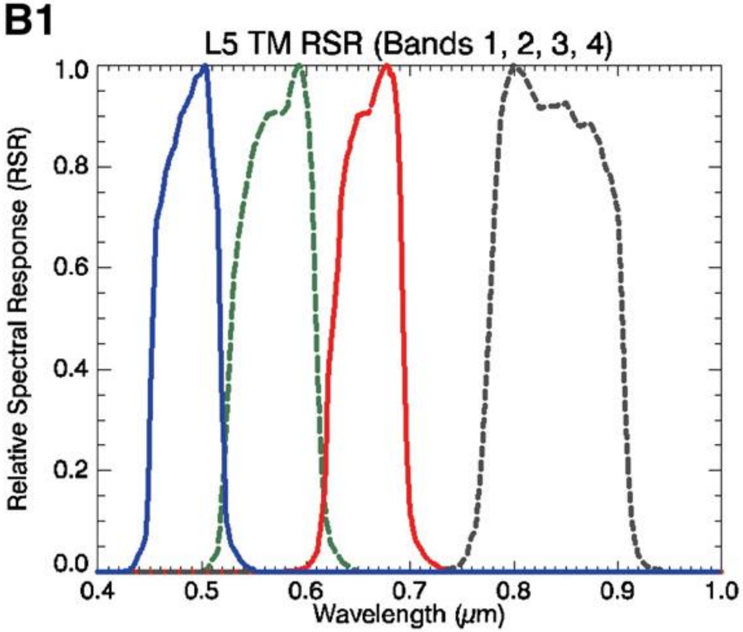
SEBAL Step 3

Albedo for the Top of Atmosphere (α_{toa})

Albedo is the ratio of reflected to incident solar (short wave) radiation at the surface.

$$\alpha_{toa} = \Sigma\,(\omega_\lambda \times \rho_\lambda)$$

$$\omega_\lambda = \frac{ESUN_\lambda}{\Sigma\, ESUN_\lambda}$$



where ω_λ is the weighting coefficient for a particular band.

SEBAL Step 4

Surface Albedo

Adjusting the α_{toa} for atmospheric transmittance

$$\alpha = \frac{\alpha_{toa} - \alpha_{path\_radiance}}{\tau_{sw}^2}$$

where, $\alpha_{path\_radiance}$ is the additional reflectance that is absorbed by sensors above the TOA because a portion of R_s is reflected to space before it reaches the surface of the earth, usually given as 0.03.

$\tau_{sw} = 0.75 + 2 \times 10^{-5} z$,

where, z being the altitude in "m" above mean sea level, and τ_{sw} is the one-way atmospheric radiation transmittance.

SEBAL Step 5

Normalized Difference Vegetation Index (NDVI)

$NDVI = (\rho_4 - \rho_3)/ (\rho_4 + \rho_3)$

Where, ρ_4 and ρ_3 are surface reflectance values in the near infra-red (NIR) and red (R) bands, respectively.

SEBAL Step 6

Thermal infrared surface emissivity (ε_s)

$$\varepsilon_s = 1.009 + 0.047 \ln(NDVI)$$

The equation above is for $NDVI > 0$

For agricultural crops, $\varepsilon_s \sim 0.97\text{-}0.98$

For bare soils, $\varepsilon_s \sim 0.93$

For snow; $\alpha > 0.47$, $\varepsilon_s = 0.999$

For water; $NDVI < 0$, $\varepsilon_s = 0.999$

SEBAL Step 7

Surface (radiometric) Temperature (T_s, K), for ***Landsat 5 and 7***:

$$T_{bb} = \frac{K_2}{\ln\left(\frac{K_1}{L_6}+1\right)}$$

$$T_S = \frac{T_{bb}}{\varepsilon_S^{0.25}}$$

where, T_{bb} is surface brightness temperature (K), TOA

K_1 and K_2 are satellite/sensor specific coefficients

L_6 is the same as L_λ or thermal band radiance value

For L5 TM, K_1 and K_2 are **607.76** and **1260.56,** respectively

For L7 ETM+, K_1 and K_2 are **666.09** and **1282.71**

SEBAL Step 8

Net Radiation (R_n, W/m^2)

$$R_n = (1 - \alpha) R_s + \varepsilon_a \sigma T_a^4 - \varepsilon_s \sigma T_s^4$$

R_s = incoming shortwave solar radiation, W/m^2
$R_s = G_{sc} \times \cos\theta_s \times d_r \times \tau_{sw}$ (estimated for cloud-free conditions)

G_{sc} solar constant (1367 W/m^2)
d_r inverse squared relative Earth-Sun distance (f(DOY))
τ_{sw} one-way transmittance
ε_a atmospheric emissivity = $1.08\,(-\ln \tau_{sw})^{0.265}$
σ is the Stefan-Boltzman constant (5×10^{-8} W/m^2/K^4)
where, $\mathbf{T_a}$ is taken as $\mathbf{T_{cold}}$ for a well watered vegetated (Ag) surface pixel.

SEBAL Step 9

Soil heat flux (G, W/m^2)

Recommended in Bastiaanssen et al. (2000), for vegetation

$G = (T_s - 273.15)(0.0038 + 0.0074\alpha)(1 - 0.98NDVI^4)\ R_n$

where, T_s= surface temperature (K), and α is surface albedo.

Flag for clear, deep water and snow:

If NDVI<0; assume clear water, $G/R_n = 0.5$

If $T_s < 4°C$ and $\alpha > 0.45$; assume snow, $G/R_n = 0.5$

SEBAL Step 10

Surface roughness for momentum transfer (Z_{om})

Z_{om} is defined as the height above the “zero plane displacement” where the wind speed tends to zero within the vegetation surface.

For agricultural fields, $z_{om} = 0.123\ h_c$, where h_c is the vegetation height (m)

To obtain z_{om} for each pixel then in SEBAL it would be a function of NDVI

Z_{om} = exp(a x NDVI)+b

Example: a = 0.9648, b = -3.3356

SEBAL Step 11

Sensible Heat Flux (H)

$H = (\rho \times c_p \times dT)/r_{ah}$

r_{ah} = the aerodynamic resistance to heat transport (s/m)

C_p is the specific heat of the air (1004 J/kg/K)

ρ is the air density (kg/m^3)

dT is the near surface temperature difference (K)

SEBAL Step 11 (cont.)

$$r_{ah} = \frac{\ln(\frac{z_2}{z_1})}{u_* \times k}$$

where, z_1 and z_2 are near surface levels, 0.1 m and 2 m respectively
k is the von Karman constant, 0.4
u_* is the friction velocity

$dT = T_o – T_a = T_s - T_a$

T_o and T_a are the surface aerodynamic and air temperatures, unknown

SEBAL assumes a linear relationship between T_s and dT

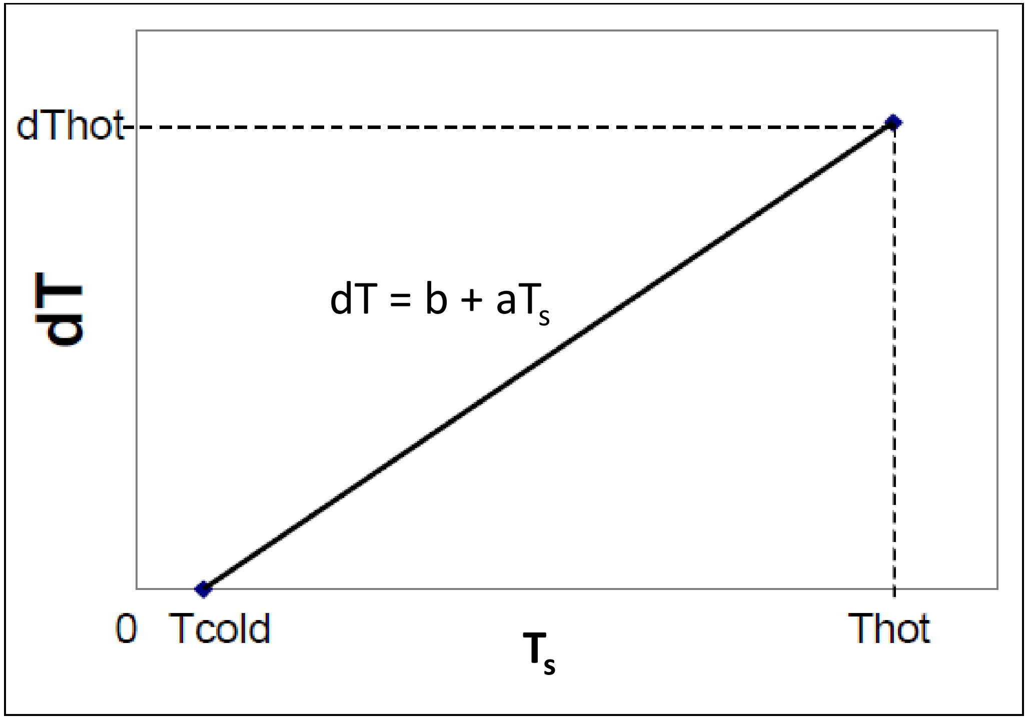
$dT = T_1 – T_2$, where T_1 is the temperature at Z_1 and T_2 is the air temperature at Z_2.

SEBAL Step 11 (cont.)

SEBAL fixes dT at two "anchor" pixels:

- At the "cold" pixel:
  - **H_{cold} = 0 (assumed)**
  - $dT_{cold} = 0$
  - First pair $(T_s, dT)_{\_cold}$

- At the "hot" pixel:
  - **$H_{hot} = (R_n - G - \lambda ET)_{hot}$**
  - where $\lambda ET_{hot} = 0$
  - $dT_{hot} = H_{hot} \times r_{ah} / (\rho \times c_p)$
  - Second pair $(T_s, dT)_{\_hot}$



Selection of anchor pixels

- To select the wet pixel, look for the lowest temperature pixels. SEBAL initially selected a cold/wet pixel in a water body surface (lake, river, etc.). It is better to select an agricultural area.

- To select the hot pixel, look for pixels with the highest temperature values,

- It is better to look for hot/dry pixels in an agricultural area that is very dry (no ET) than manmade surfaces or completely bare soils.

SEBAL Step 11, cont'd

Friction velocity (u_*) & r_{ah} (neutral)

To obtain friction velocity for each pixel, first compute it for the weather station site (grass/alfalfa). Then, use the obtained u_* value to extrapolate the weather station measured wind speed (at 2m height) and extrapolate it to a blending height of 200 m (U_{200}). Subsequently, use the U_{200} value and the distributed Zom values to obtain a u_* value for each pixel.

$$u_* = \frac{k u_x}{\ln(\frac{z_x}{z_{om}})}$$

u_x is wind speed (m/s) at height z_x above ground

Z_{om} is the momentum roughness length (m)

Friction velocity for each pixel

Friction velocity u_*, m/s:

$$u_{200} = u_{*\_station} \frac{\ln(\frac{200}{z_{om\_station}})}{k}$$

Then:

$$u_{*\_pixel} = \frac{k u_{200}}{\ln(\frac{200}{z_{om\_pixels}})}$$

Aerodynamic resistance

Aerodynamic resistance (s/m) to heat transport (r_{ah_pix}) for each pixel (neutral atmospheric conditions):

$$r_{ah\_pixel} = \frac{\ln(\frac{z_2}{z_1})}{u_{*\_pixel}\, k}$$

SEBAL Step 12

Sensible Heat Flux (H, W m^{-2})

Compute initial H using r_{ah} from previous step for neutral atmospheric conditions

$$H = (\rho \times c_p \times dT_{\_pixel})/r_{ah\_pixel}$$

SEBAL Step 13

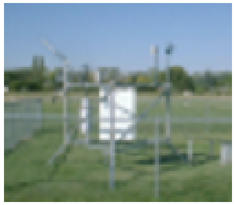
1ST Stability correction for u_* & r_{ah} using MOST:

$$u_* = \frac{k \cdot u_{200}}{\ln\left(\frac{200}{z_{om}}\right) - \Psi_{m(200m)}}$$

$$r_{ah} = \frac{\ln\left(\frac{z_2}{z_1}\right) - \Psi_{h(z_2)}}{u_* \cdot k}$$

- Ψ_m is the stability factor for momentum transfer (m)
- Ψ_h is the stability factor for heat transfer (m)
- New values for dT are then computed for the anchor pixels
- New values of **a** and **b** are computed for **dT**
- A corrected value of H is computed
- The stability correction is repeated until H stabilizes **(STEPS 14-19)**
- The Monin-Obukhov Similarity Theory (MOST) correction is used to determine the stability factors.

Atmospheric stability correction is repeated until H stabilizes (STEPS 14-19)



Weather station

u, z_x, z_{om}, u_*

wind speed at 200 meters

$$u_{200} = u_* \frac{\ln\left(\frac{z_{200}}{z_{0m}}\right)}{k}$$

friction velocity at each pixel

$$u_* = \frac{k u_{200}}{\ln\left(\frac{z_{200}}{z_{0m}}\right)}$$

r_{ah} for each pixel

$$r_{ah} = \frac{\ln\left(\frac{z_2}{z_1}\right)}{u_* \times k}$$

Cold Pixel	Hot Pixel
$H_{cold} = Rn - G - \lambda ET_{cold}$	$H_{hot} = Rn - G$
$dT_{cold} = H_{cold} * r_{ah} / (\rho Cp)$	$dT_{hot} = H_{hot} * r_{ah} / (\rho Cp)$

dT for each pixel

$$dT = aTs + b$$

H for each pixel

$$H = \rho Cp \frac{dT_a}{r_{ah}}$$

$$L = -\frac{\rho Cp u_*^3 T_s}{k g H}$$

Detail on MOST application in article uploaded

$$\psi_{m(200)}$$

$$\psi_{h(z2)}$$

$$u_* = \frac{k u_{200}}{\ln\left(\frac{z_{200}}{z_{0m}}\right) - \Psi_{m(200)}}$$

$$r_{ah} = \frac{\ln\left(\frac{z_2}{z_1}\right) - \Psi_{h(z_1)}}{u_* \times k}$$

SEBAL Step 20

Instantaneous LE, in W/m^2, at the time of remote sensing platform overpass:

$$LE = Rn - G - H$$

$$ET_{inst} = t \times LE/(\lambda_v \times \rho_w)$$

t = time constant (number of seconds in a given period, e.g. 3,600 sec if ET per hour)

$\lambda_v = (2.501\text{-}0.00236(T_{s\_cold} - 273.15)) \times 10^6$ (J/kg)

$\rho_w = 1$ Mg/m^3

SEBAL Step 21

$$EF_i = \left(\frac{LE}{R_n - G}\right)_{\text{i}}$$

$$EF_i = EF_d = \left(\frac{LE}{R_n - G}\right)_d$$

- EF is the evaporative fraction calculated for the time of the image. This approach is based on the self-preservation theory of daytime fluxes which states that the ratio between the latent heat flux (LE) and the available energy (Rn – G) remains constant during the day.
- Therefore it is assumed that the EF estimated at the time of remote sensing platform overpass will be valid to represent the EF for the entire day.
- This assumption allows for the extrapolation of instantaneous LE values to daily ones, in SEBAL.

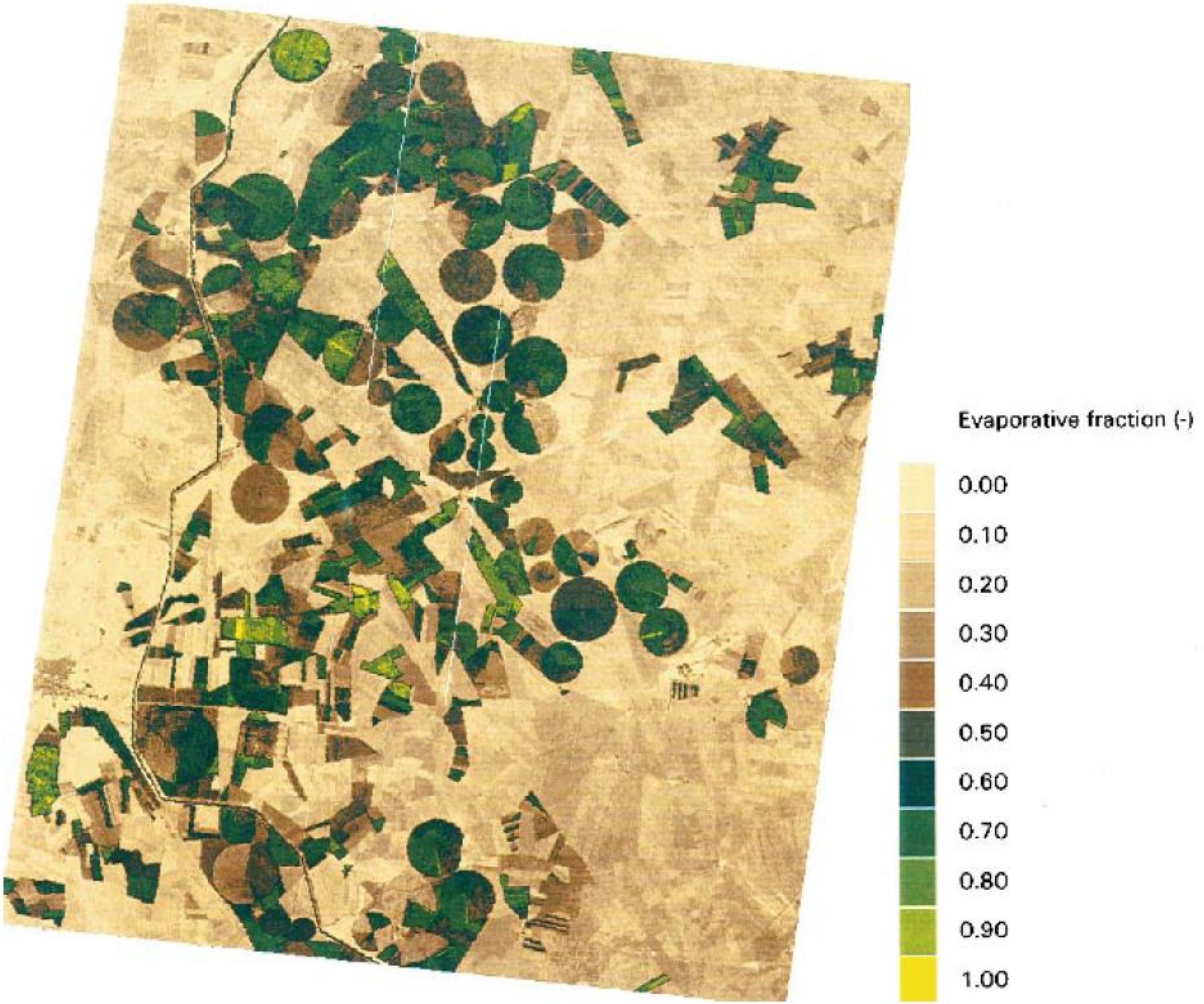


Fig. 11. NS001-based evaporation map for Barrax estimated with the SEBAL parameterization, June 29, 1991. Time integration of instantaneous to 24 hour values was realized by holding evaporative fraction constant and adjust the net radiation.

SEBAL Step 22

Daily R_n calculation in W/m^2,

$$R_{nd} = (1 - \alpha)\, R_{ad}\, \tau_{sw} - 110\, \tau_{sw}$$

Daily net radiation (R_{nd}) under all-day clear sky conditions.

R_{ad} is the daily extraterrestrial radiation, α is the surface albedo, and τ_{sw} is the atmospheric transmittance.

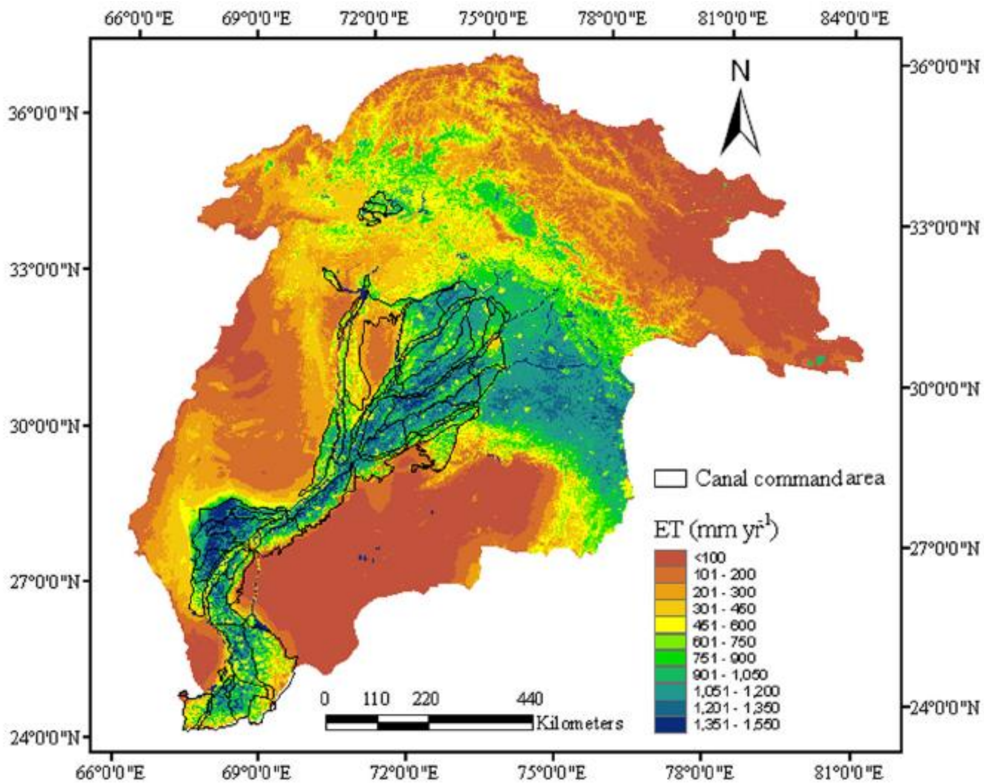
To account for haze and cloudiness it is better to replace the terms $R_{ad}\, \tau_{sw}$ in the first part of the equation by a locally measured daily average incoming short wave solar radiation (R_s) and the τ_{sw} could be estimated as the ratio R_s/R_{ad}.

SEBAL Step 23

Daily ET calculation (ET_d)

$$ET_d = 86{,}400 \frac{EF_i(R_n - G)_d}{\lambda_v \rho_w}$$

In SEBAL, the total soil heat flux for an entire day is assumed to tend to zero for vegetation and most bare soils.



$$ET_d = 86{,}400 \frac{EF_i \cdot R_{nd}}{\lambda_v \cdot \rho_w}$$