A scientific description of SEBAL procedure

1 Overview

The Surface Energy Balance Algorithm for Land (SEBAL) is an image-processing model comprised of 25 computational steps that calculate the actual (ET_{act}) and potential evapotranspiration rates (ET_{pot}) as well as other energy exchanges between land and atmosphere. The key input data for SEBAL consists of spectral radiance in the visible, near-infrared and thermal infrared part of the spectrum (see **Figure 1** and **Figure 2**). SEBAL computes a complete radiation and energy balance along with the resistances for momentum, heat and water vapor transport for every individual pixel. The resistances are a function of state conditions such as soil water potential (and thus soil moisture), wind speed and air temperature and change from day-to-day.

Satellite radiances will be converted first into land surface characteristics such as surface albedo, leaf area index, vegetation index and surface temperature. These land surface characteristics can be derived from different types of satellites. First, an instantaneous evapotranspiration is computed, that is subsequently scaled up to 24 hours and longer periods.

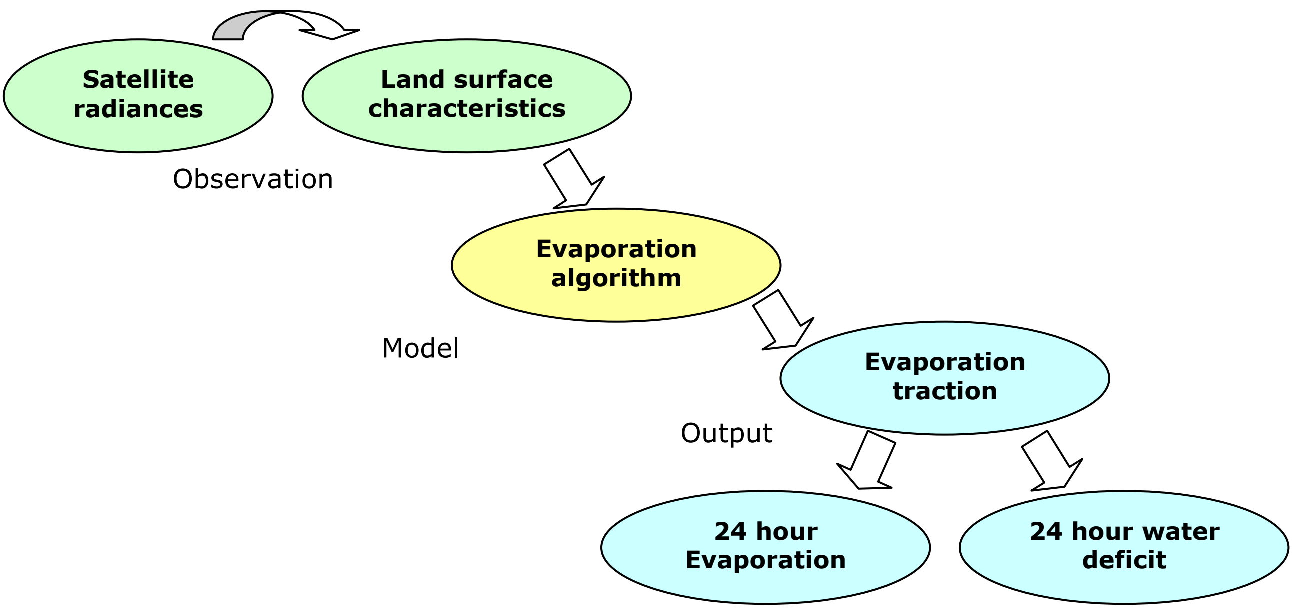

Figure 1 Flow chart of the principal steps in SEBAL to derive instantaneous 24-hour ET_{act} and ETpot values

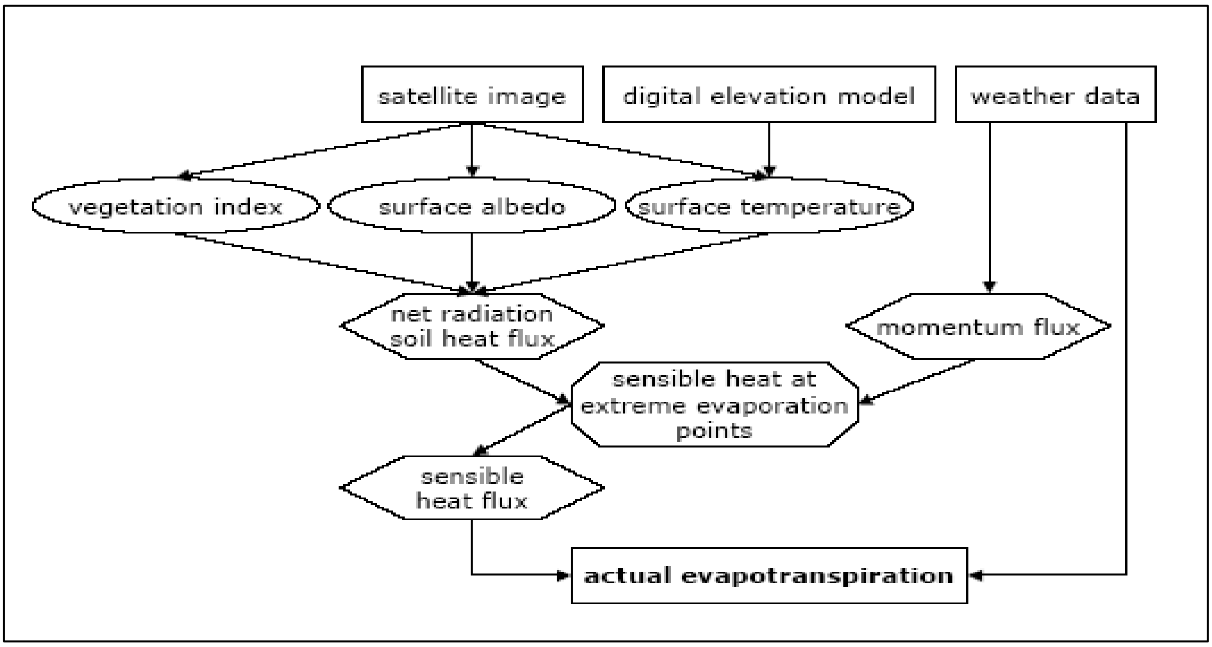

Figure 2 Schematic view of energy balance and ET computations with SEBAL

2 Data requirements

In addition to satellite images, the SEBAL model requires the following routine weather data parameters:

- Wind speed
- Humidity
- Solar radiation
- Air Temperature

There is no data on land cover, soil type or hydrological conditions required to apply SEBAL.

3 SEBAL Evapotranspiration

The primary basis for the SEBAL model is the surface energy. The instantaneous ET_{act} flux is calculated for each cell of the remote sensing image as a 'residual' of the surface energy budget equation:

$$ET = R_n - G - H \qquad (1)$$

where; ET is the latent heat flux (W/m^2), R_n is the net radiation flux at the surface (W/m^2), G is the soil heat flux (W/m^2), and H is the sensible heat flux to the air (W/m^2) (see Figure).

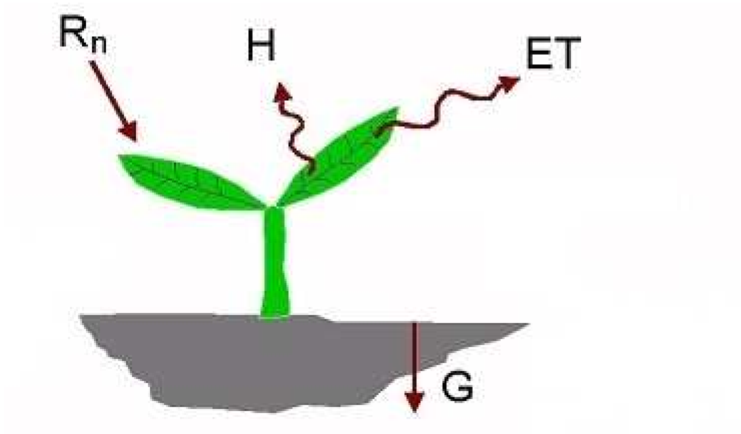

Figure 3 Surface Energy Balance

R_n represents the actual radiant energy available at the surface. It is computed by subtracting all outgoing radiant fluxes from all incoming radiant fluxes (**Figure 4**). This is further specified in the surface radiation balance equation:

$$R_n = R_{S\downarrow} - \alpha R_{S\downarrow} + R_{L\downarrow} - R_{L\uparrow} - (1-\varepsilon_0)R_{L\downarrow} \quad (2)$$

where RS↓ is the incoming short-wave radiation (W/m^2), a is the surface albedo (dimensionless), RL↓ is the incoming long wave radiation (W/m^2), RL↑ is the outgoing long wave radiation (W/m^2), and εo is the surface thermal emissivity (dimensionless).

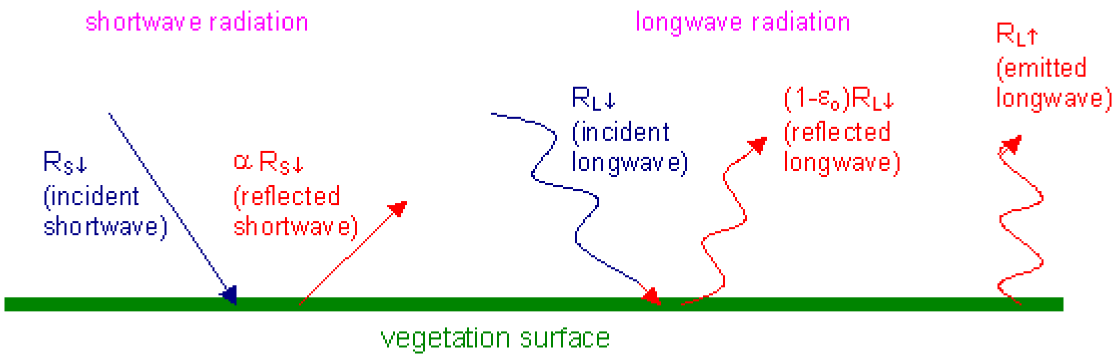

Figure 4 Surface Radiation Balance

In Eq. (2), the amount of net short-wave radiation (RS↓ - aRS↓) that remains available at the surface, is a function of the surface albedo (a). The broad band surface albedo a is derived from the narrow band spectral reflectances a(λ) measured by each satellite band. The incoming short-wave radiation (RS↓) is computed using the solar constant, the solar incidence angle, a relative earth-sun distance, and a computed broad band atmospheric transmissivity. This latter transmissivity can be estimated from sunshine duration or inferred from pyranometer measurements (if available). The incoming long wave radiation (RL↓) is computed using a modified Stefan-Boltzmann equation with an apparent emissivity that is coupled to the shortwave atmospheric transmissivity and a measured air temperature. Outgoing long wave radiation (RL↑) is computed using the Stefan-Boltzmann equation with a calculated surface emissivity and surface temperature. Surface temperatures are computed from the satellite measurements of thermal radiances.

In Eq. (1), the soil heat flux (G) and sensible heat flux (H) are subtracted from the net radiation flux at the surface (Rn) to compute the "residual" energy available for evapotranspiration (λE). Soil heat flux is empirically calculated as a G/Rn fraction using vegetation indices, surface temperature, and surface albedo. Sensible heat flux is computed using wind speed observations, estimated surface roughness, and surface to air temperature differences that are obtained through a sophisticated self-calibration between dry ($\lambda E \approx 0$) and wet ($H \approx 0$) pixels. SEBAL uses an iterative process to correct for atmospheric instability caused by buoyancy effects of surface heating.

The λE time integration in SEBAL is split into two steps. The first step is to convert the instantaneous latent heat flux (λE) into daily $\lambda E24$ values by holding the evaporative fraction constant. The evaporative fraction EF is:

$$EF = \lambda E / (Rn - G) \qquad (-) \qquad (3)$$

Field measurements under various environmental circumstances have indicated that EF behaves temporally stable during the diurnal cycle. Since EF ~ EF24, i.e. the 24 hour latent heat flux can be determined as:

$$\lambda E24 = EF\ Rn24 \qquad (W/m^2) \qquad (4)$$

For simplicity, the 24 hour value of G is ignored in Eq. (4). The second step is the conversion from a daily latent heat flux into monthly values, which has been achieved by application of the Penman-Monteith equation:

$$\lambda EPM = (sa\ Rn24 + \rho acp\ \Delta e/ra) / (sa + \gamma\ (1 + rs/ra)) \qquad (W/m^2) \qquad (5)$$

where sa (mbar/K) is the slope of the saturated vapor pressure curve, ρacp (J/m^3 K) is the air heat capacity, Δe (mbar) is the vapor pressure deficit, γ (mbar/K) is the psychrometric constant and ra (s/m) is the aerodynamic resistance. The parameters sa, Δe and ra are controlled by meteorological conditions, and Rn and rs by the hydrological conditions.

The SEBAL computations can only be executed for cloudless days. The result of $\lambda E24$ from Eq. (4) has been explored to convert the Penman-Monteith equation (5) and to quantity rs inversely using $\lambda E24 = \lambda EPM$. The spatial distribution of rs so achieved, will consequently be used to compute $\lambda E24$ by means of Eq. (5) for all days without satellite image available (Bastiaanssen and Bandara, 2001). The total ET_{act} for a given period can be derived from the longer term average λE flux by correcting for the latent heat of vaporization and the density of water.

4 SEBAL Biomass growth

The biomass production routine in SEBAL is based on solar radiation absorption by chlorophyll and the conversion of this energy into a dry matter production by means of a light use efficiency:

$$Bio = \int APAR(t)\ e(t)\ dt \qquad (kg/ha) \qquad (6)$$

The absorption of solar radiation (APAR) for photosynthesis depends on global radiation and light interception. The second component of Eq. (6) describes the light use efficiency e(t) that converts energy into dry matters.

Photosynthetic Active Radiation (PAR) (0.4 to 0.7 μm) is part of the short wave solar radiation (0.3 to 3.0 μm) that is absorbed by chlorophyll for photosynthesis in the plants. PAR is thus a fraction of the incoming solar radiation, Rs↓. The PAR value describes the total amount of radiation available for photosynthesis if leaves intercept all radiation. This is a rather theoretical value, because leaves transmit and reflect solar radiation. Only a fraction of PAR will be absorbed by the canopy (APAR) and used for carbon assimilation. APAR can be approximated as a fraction of the PAR using the Normalized Difference Vegetation Index (NDVI):

$$APAR = (-0.161 + 1.275\ NDVI) * PAR \qquad (W/m^2) \qquad (7)$$

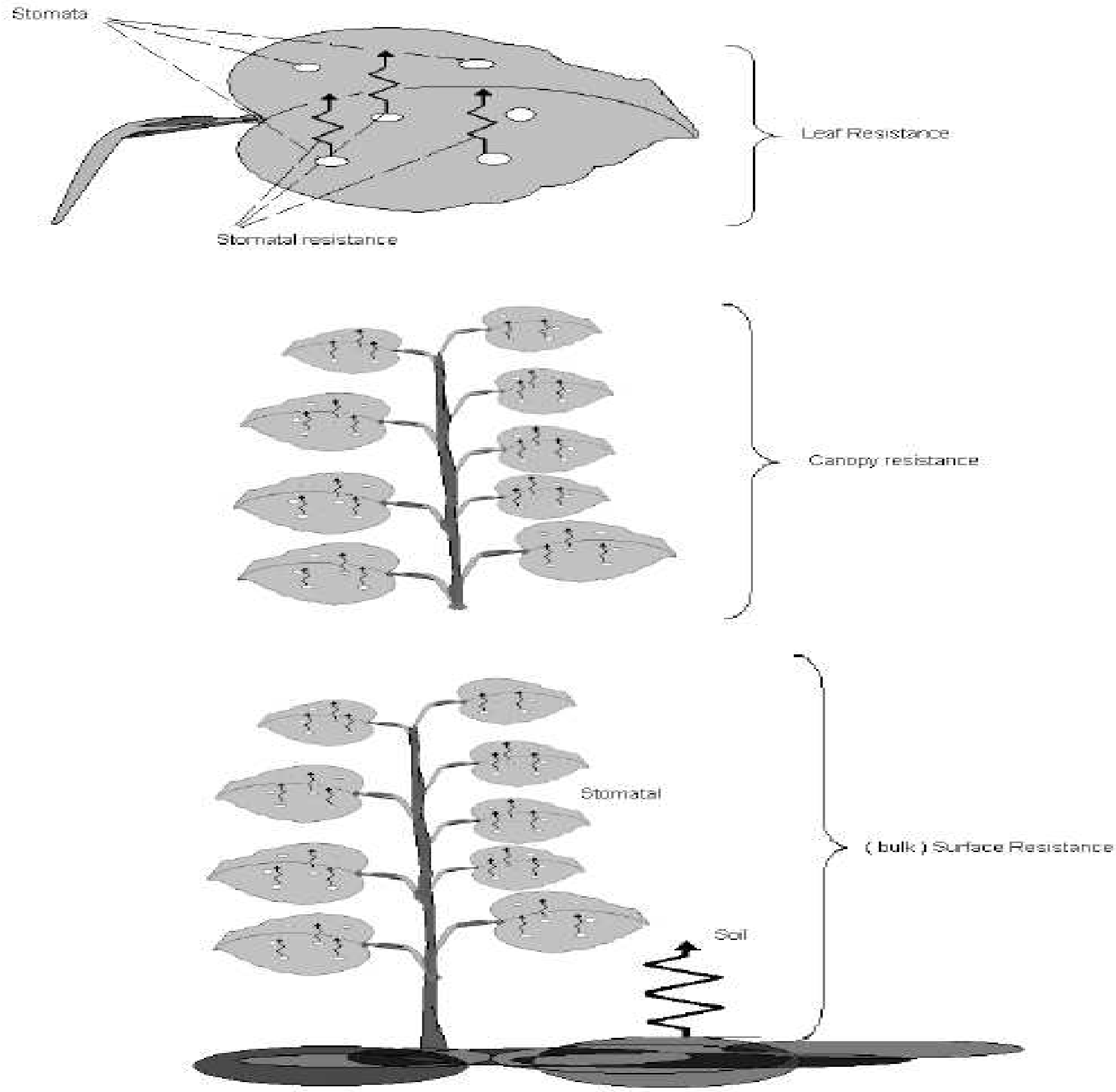

Figure 5 Various resistances that control the evapotranspiration rate

The light use efficiency describes the climate impact and environmental stress on crop growth. Carbon dioxide is obtained from the atmosphere through the stomata's. The waste products of photosynthesis, oxygen and water vapor, are dispelled from the plant thought the same stomata's into the air. The light use efficiency is coupled to the stomatal aperture that is expressed into the bulk surface resistance. The mathematical-biological description of the bulk surface resistance reads as:

$$r_s = \frac{r_{s\min}}{LAI \quad F_1(T_a)F_2(\Delta e)F_3(h_{rw})} \qquad (s/m) \qquad (8)$$

where r_{smin} (s/m) is the leaf or bulk stomatal resistance, LAI (dimensionless) is the Leaf Area Index, $F_1(T_a)$ represents a function that describes the effect of air temperature on r_s, the function $F_2(\Box_e)$ represents the effect of the vapor pressure deficit on the stomatal aperture and the function $F_3(h_{rw})$ is the effect of the soil water potential on r_s. By holding the soil water potential constant between two consecutive satellite overpasses, and making F_1 and F_2 variable, r_s can be re-computed for every individual day. In this case study in Sirsa, all F_1, F_2 and F_3 values have been kept constant in between consecutive NOAA acquisition days.

When the stomata's close due to environmentally induced lower leaf water potentials with limiting expansion of the guard cells, light is no longer effectively converted into dry matter because carbon is absent in sufficient quantities. A resistance scalar is used to quantify the day-to-day value of the light use efficiency *e*(t). It is from experimental studies known that the light use efficiency has a prescribed maximum that depends on c3 and c4 crops. This maximum value is multiplied by the resistance scalar to obtain the actual value for light use efficiency:

$$e(t) = e_{max} * f(r_s) \qquad \text{(gr/MJ)} \qquad (9)$$

The SEBAL model formulation for crop growth is on large tracks similar to most numerical crop growth simulation models and global scale ecological production models. A significant difference, though, is that crop development due to soil type, prevailing water management conditions and farmer practices is not computed, but prescribed through satellite measured NDVI and temperature time profiles.