Evapotranspiration of crops by remote sensing using the energy balance based algorithms

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Abstract: Amongst the most crucial information in water balance assessment, is the evapotranspiration (ET) of the plants, especially field crops. A large literature is available on potential and reference ET, and it is a modeling exercise to assess the crop areas, the level of effective development and the water stress found under the pre-supposed field conditions. This becomes increasingly difficult when variables are varying in time, space and crop types.

Models to calculate ET have very early faced the most difficult parameter, the crop itself. Knowing about the crop was the necessity for calculating anything about it. When facing a water basin of very large area, agro-climatically transient in its various parts, treating the ET calculation by the energy-balance becomes interesting. Information about the vegetation cover is indeed minimal and often very well provided by satellite information.

Some earlier experience of water depletion for crops is briefly overviewed for PRC, The Philippines and Uzbekistan, with some water depletion results. Some various satellites are used, Landsat 7 ETM+, NOAA AVHRR, TERRA MODIS and TERRA ASTER. Only satellites able to provide temperature measurements are fulfilling the requirements of such analysis. Some meteorological satellites are also used for calculating ET in Global Climatological Models, but are of too coarse pixel resolution for the application to crop ET per se.

Issues of cloud cover have also been raised, and addressed most of the time positively. Validations of such monitoring algorithms have been widely performed and are always found acceptable.

It is concluded that even if research is still actively tackling the calculation of ET by means of remote sensing measurements, the numerous applications of the different energy balance models available show that it has long passed the initial development and can be used fairly confidently.

Introduction

Water resources have to be managed very clearly from the water basin to the irrigated crops, eventually reaching to smaller areas and users. Measuring the evapotranspiration is of highest importance for understanding and eventually intervening into the water cycle of natural systems, especially in the water balance of the different critical users of water, like irrigated areas and their field crops. A large amount of literature is available on potential and reference ET, and it is a modeling exercise to assess the crop areas, the level of effective development and the water stress found under the pre-supposed field conditions. This becomes increasingly difficult when variables are varying in time, space and vegetation/crop types.

Models to calculate ET have very early faced the most difficult parameter, the crop itself. Knowing about the crop was the necessity for calculating anything about it. When facing a water basin of large area, agro-climatically transient in its various parts, treating the ET calculation by the energy-balance becomes interesting. Information about the vegetation cover is indeed minimal and often very well provided by satellite information.

Remote sensing has come out, over the last decades, with methods for calculating the actual evapotranspiration (ETa) based on the equilibrium between the radiation balance and the energy balance at the surface of the Earth.

Objective

The objective of this paper is to put forward the energy balance in the context of satellite remote sensing for the purpose of monitoring the evapotranspiration of irrigated areas and their crops.

The energy balance process and remote sensing science

The Radiation coming from the sun can be split into Longwave and Shortwave. The Longwave radiation does heat particular ground features that will eventually be released after a certain amount of time. The Shortwave radiation is instantaneously reflected by ground features according to their Albedo characteristics.

$$Rn = K^{\downarrow} - K^{\uparrow} + L^{\downarrow} - L^{\uparrow} \qquad (W/m^2) \qquad \text{Equation 1}$$

This rather simple system of radiation balance is considering the ground elements as a layer of a given height, responding uniformly to a radiation stimulus. This concept has two direct advantages, the first one is to simplify in-layer structural ground element interactions, the second one is that it is very well fitting the ideal description of a satellite remote sensing and its ground sampling unit: the pixel.

The Energy Balance partitioning is summarized at an instant time *t* (at the time of satellite overpass) by the following equation:

$$Rn = G_0 + H + \lambda E \qquad (W/m^2) \qquad \text{Equation 2}$$

where *Rn* is the net radiation emitted from the Earth surface (W/m^2), G_0 is the soil heat flux (W/m^2), *H* is the sensible heat flux (W/m^2), λE is the latent heat flux, being the energy necessary to vaporize water (W/m^2). Generally lateral fluxes are not considered when dealing with Remote Sensing images because of their spatial cover capturing the instantaneous energy balance system. Even when transforming the energy balance components for a daily extrapolation of the values, lateral exchanges between pixels are found either in one pixel or in the neighboring ones, extrapolation does not expose lateral values yet encompasses them.

$$G_0 = \frac{\rho_s C_s (T_0 - T_s)}{r_s} \qquad (W/m^2) \qquad \text{Equation 3}$$

Heat flow into the soil, G_0, is driven by a thermal gradient in the uppermost topsoil (Parodi, 2000). It is a conduction flux through the soil matrix. This gradient varies with the state of the vegetation covering the soil that is influencing the light interception by the soil surface. The radiative heating of the topmost layer is then directly modifying the surface temperature and thermal gradient in the top layer. The Sensible Heat flux (*H*) is a convection flux through the atmosphere layers, coming from the surface skin boundary layer with the topmost soil/vegetation layer.

$$H = \frac{\rho_{air} C_p (T_0 - T_a)}{r_{aH}} \qquad (W/m^2) \qquad \text{Equation 4}$$

The energy necessary to vaporize water under given atmospheric conditions is especially ruled by the resistance to vaporization parameter (r_v)

$$\lambda E = \lambda \left(\frac{\rho_{vs} - \rho_{va}}{r_v} \right) \qquad (W/m^2) \qquad \text{Equation 5}$$

After Menenti (2000), the milestone in the development of remote sensing methods to determine actual evaporation through the surface heat balance approach was the linear relationship method proposed by Jackson et al. (1977):

$$\int_{day} (Rn - \lambda E) dt = B (T_s - T_a)^n \qquad (mm/day) \qquad \text{Equation 6}$$

Where B is a constant and n=1. The excess available energy on the left side of the equation is proportional to the difference between the surface and air temperature. [Ts – Ta] (dT) is also the expression of the resistance to sensible heat transfer, which, in this case would be considered constant. That assumption on which this first equation was based is obviously disputable over non-homogeneous land cover. This was observed by Menenti (1984) in terms of significant Rn changes over heterogeneous land, while Stone et al. (1975) had similar changes on temperature, but this time in the temporal dimension.

Eventually some modification where incorporated to the linear relationship equation, especially some improvement of the calculation of the radiometric surface temperature. This step was a temporary development, yet critical when Carlson and Buffum, (1989), in their proposition to relate (Rn-λE) to the rate of increase in surface temperature during the morning, put forward that the newly developed model of the equation was sensitive to wind speed and surface roughness.

Adding to the above, it was observed (Price, 1990) that the vegetation cover and the surface temperature can both contribute in a better way to estimate actual evaporation. Carlson et al. (1995) proposed to modify the linear relationship so as to include spatial variability of vegetation cover, changing B and n.

An other line of research is the use of Soil Vegetation Atmosphere Transfer models (SVAT) that used essentially large amount of numerical modeling of ground characteristics along with some quantifiable from the area studied. This was complemented by thermal infrared imagery from the satellite images. Inversion of such model (Taconet and Vidal-Madjar, 1988) would infer heat fluxes at land surface. The large amount of information required lead to the incorporation of satellite images products as parameters of the models (Moran and Jackson, 1991). Using Planetary Boundary Layers models to define a blending height where spatial variation disappears due to horizontal mixing, has been proposed by Wierenga (1986) and used by Brutsaert et al. (1992).

The current trends in remote sensing applications to calculate the heat balance equation terms lay in improved accuracy of observations and parameterizations. Still the baseline is that the temperature is giving the most critical information about the evaporation, especially critical (at given available energy, PBL conditions and including the aerodynamic properties of the surface) are the maximum evaporation and the corresponding range of minimum to maximum surface temperature. Further research has proven that under specific conditions, the T_{rad} could be related to NDVI (Goward et al., 1985) and to Surface Albedo (Menenti et al., 1986). This developed into the concept of Vegetation Index /Temperature Trapezoid (VITT, Moran et al., 1994), observing the temperature gives a measure of evaporation, relative to maximum evaporation, at constant green vegetation.

These methods above, however, require quite complex models to construct the case-specific algorithms which make direct use of remote measurements of spectral radiances. A lot of the effort is now concentrating into increasing the accuracy of radiant fluxes, even if Surface Albedo can easily be estimated by common sensors (enabling the calculation of the shortwave net radiation), it takes more specific sensors to estimate the longwave component of the radiation balance. Surface Albedo and temperature can also be the basis for estimates of the upwelling components, while the downwelling components are based on meteorological data (Moran et al., 1989). Soil heat flux can be estimated by the ratio G/Rn through spectral indices (Choudhury et al., 1994), or by semi-empirical equation including Rn, the surface Albedo, the surface temperature, NDVI and the area average Surface Albedo (Bastiaanssen, 1995). The parameterization of turbulent fluxes is having a large part of research in itself, two main parameters are used generally, the Leaf Area Index (LAI, inferred from NDVI) and the aerodynamic resistance (r_a, for momentum and for heat transport). On the subject of estimating the latest, Menenti (2000) concludes that relatively simple models of heat transfer at the land atmosphere interface can be sufficiently accurate if a few key–variables can be determined with sufficient accuracy and capturing the fundamental physics of the process, as in the case of the difference between the aerodynamic and radiation surface temperatures (T_{aero}-T_{rad}). Lastly, some methods exploit image context (Price, 1990; Bastiaanssen, 1995), albeit having certain advantages (like taking advantage of range availability for deriving equations) also are restrictive to areas and often contextual to image conditions, making automation of processes a major constraint.

Even if the Net radiation and Soil heat flux parts of the energy balance equation are relatively well known and estimated from a remote sensing point of view, the remote sensing of the sensible heat flux and especially its most critical parameter [T_{aero}-T_{rad}] is still limited. Some authors (like Bastiaanssen, 1995) resolved this difficulty through an iterative process that balances the Monin-Obukov Length and the distribution of [T_{aero}-T_{rad}] simultaneously. Eventually some other method relates the Latent heat flux directly through some Bowen ratio measurements (i.e. Polonio and Soler, 2000).

Water consumption of crops and some common satellites

Calculation of water consumptions by remote sensing has been under high research efforts for the last 20 years, especially the energy balance models. Some reviews can be found in Kustas and Norman (1996), Bastiaanssen (1998) and Menenti (2000). Some dedicated energy-balance models like the TSEB (Norman et al., 1995), SEBAL (Bastiaanssen, 1995), SEBI (Menenti, 2000), and also some related models calculating evapotranspiration (Vidal and Perrier, 1989; Choudhury, 1994; Granger, 1997) are also available among others not mentioned here. To add to this non-extensive list, a lot of Global Climatologic Models use the energy-balance process for various outputs like ET or soil moisture (McKee et al., 2001). Typically, for crop ET monitoring, high spatial resolution satellites are required, but the list is restricted to satellites having the capacity to calculate the surface temperature, as the latent heat flux of vaporization is temperature driven. Some coarser spatial resolution satellites up to 1 Km pixel size are still used for irrigation system temporal ET monitoring. Larger spatial resolution satellites, generally for meteorological purposes, even if used largely in GCMs, are not used for crop monitoring.

The method used to illustrate this paper is estimating the actual ET using Surface Energy balance Algorithm for Land (SEBAL) by Bastiaanssen (1995), modified by Tasumi et al. (2000). SEBAL is one of the thermodynamically based models available, which partitions the sensible heat flux and the latent heat flux of vaporization. The author has originally developed SEBAL in Spain and Egypt using Landsat 5TM. Further, Roerink et al. (1997) also applied the same sensor for monitoring irrigation performance in Argentina. Water consumption of large irrigation systems has been addressed also with NOAA AVHRR in Pakistan (Bastiaanssen et al., 1999; validation in Bastiaanssen et al., 2002. Combinations of Landsat and NOAA are found in Timmermans and Meijerink (1999) where Landsat 5TM was used, and in Chemin and Alexandridis (2002) who used Landsat 7ETM+. Later on, Hafeez and Chemin (2002) applied it using TERRA/ASTER sensor and TERRA/MODIS (Hafeez et al., 2002) in the Upper Pumpanga River Integrated Irrigation System (UPRIIS), Philippines. Finally, some applications in water management in Uzbekistan are found in Chemin et al. (2002) and in Chemin and Platonov (2002).

In order to address cloud cover and to get high spatial resolution ET images, resolution improvement techniques are applied. Actual evapotranspiration images from NOAA AVHRR acquired at various dates in Zhanghe irrigation district were used in Chemin and Alexandridis (2002) together with meteorological daily reference evapotranspiration data to estimate daily evapotranspiration. A temporal integration for the May – September rice cropping season provided the seasonal actual evapotranspiration map. This information, collected at a pixel size of 1.1 km was merged together with a Landsat 7 ETM+ image acquired at a strategic moment of the cropping season. The result was a more detailed redistribution of seasonal evapotranspiration volumes to finer resolutions, while keeping the actual evapo-transpired global volume constant, before and after the merging. This provided a better located estimation of water consumption, especially for rice. Irrigated rice fields were of particular interest to the water managers, since these fields were the main cash crop of the irrigation district.

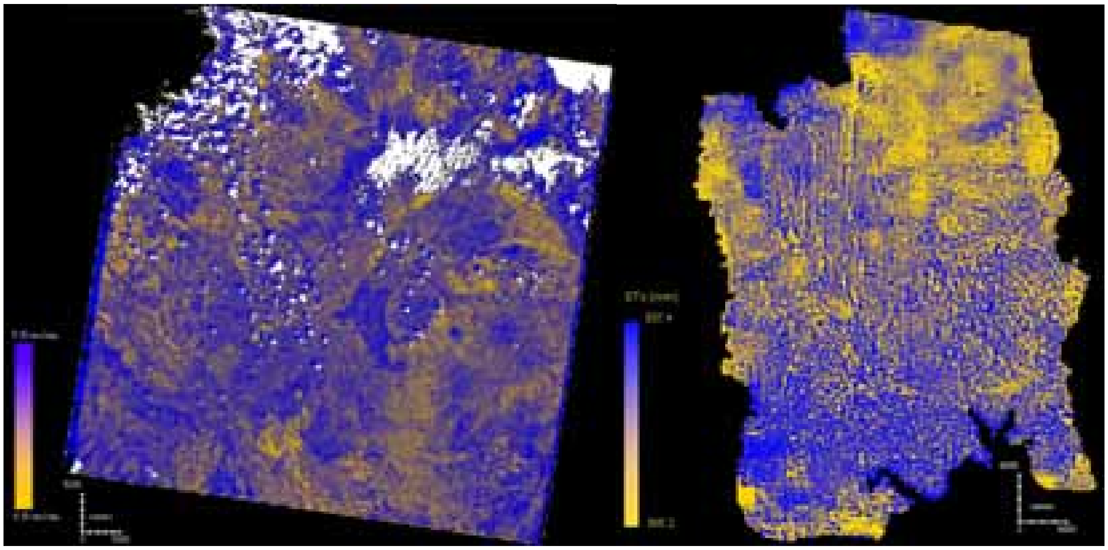
In the Ferghana Province of Uzbekistan, Chemin et al. (forthcoming) improved the spatial resolution of NOAA AVHRR following Chemin, Alexandridis and Loeve (2002), using Landsat imagery of pre-harvest satellite overpass, however not using the intra-pixel land use adjustment that was necessary in their China experiment because of the rice field sizes being smaller than a pixel of Landsat 7 ETM+. In the case of Ferghana Valley, the field sizes are encompassing a consequent amount of Landsat pixels, thus simplifying the resolution enhancement procedure from NOAA.

Although spatial resolution enhancement is interesting operationally speaking, it is still tedious to process so it would be preferable to avoid it when it may not be required. Alexandridis and Chemin (2001) found in Zhanghe Irrigation District (Hubei, PRC) that the optimum pixel size for observing evapotranspiration of rice fields was locally different than the highest spatial resolution available in their study.

It certainly brings forth the fact that medium pixel size does not hamper the contrast assessment of ET in small field type irrigation systems, or said differently: Measuring ET with medium size pixels is not incompatible with dense systems of small parcels, like the ones found in parts of PRC and South Asia. One limitation though would be the crop/irrigation system boundary delineation by medium-coarse satellite pixels. That would be less accurate area-wise and would generate some (unaccounted yet) inaccuracy in the calculation of the water balance of the irrigation system, as the local Variance of the vegetation response is found to be always increasing with the lowering of the pixel sizes in ZID (Alexandridis and Chemin, 2002). Initial indications on the ET measurement scale are that this scale effect observed in Zhanghe Irrigation District may be variable from one agro-ecosystem to another, and also from one irrigation system to another.

Crop evapotranspiration by remote sensing

Typical results of remote sensing calculation of energy-balance come in daily actual ET (Figure 1a, after Hafeez and Chemin, 2002) and Seasonal ET (Figure 1b, after Chemin, Alexandridis and Loeve, 2002), respectively an Aster processing of Central Luzon (The Philippines) and an AVHRR/Landsat data processing in Zhanghe Irrigation District, Hubei Province, PRC. Both of these locations are encompassing a large amount of irrigated rice areas.



a) b)

Figure 1: a) ET actual of february 02nd, 2001 in The Philippines (white = clouds) and b) ET actual for the rice growing season (May-September 2001) in PRC.

Some work of Bastiaanssen et al. (1999) on the Indus Basin in Pakistan gave AVHRR based water consumption of irrigated crops for irrigation management of the largest contiguous irrigation system in the world (about 16 millions hectares) and completing some validation work on yearly ET (Bastiaanssen et al., 2002). In the medium/large pixel size range, another promising sensor for covering large area with ET measurements is Modis (on platform Terra) having some spectral/radiometric/spatial/geometric advantages to the AVHRR sensors.

Spatio-temporal analysis of irrigation systems in the Uzbekistan study of Chemin and Platonov (2002) has shown the sensitivity to track down elements of the cropping calendar of a cotton-based irrigation system from Public remote sensing data. Additionally some water stress indications per irrigation system are easily recognized on the beginning of July (Figure 2).

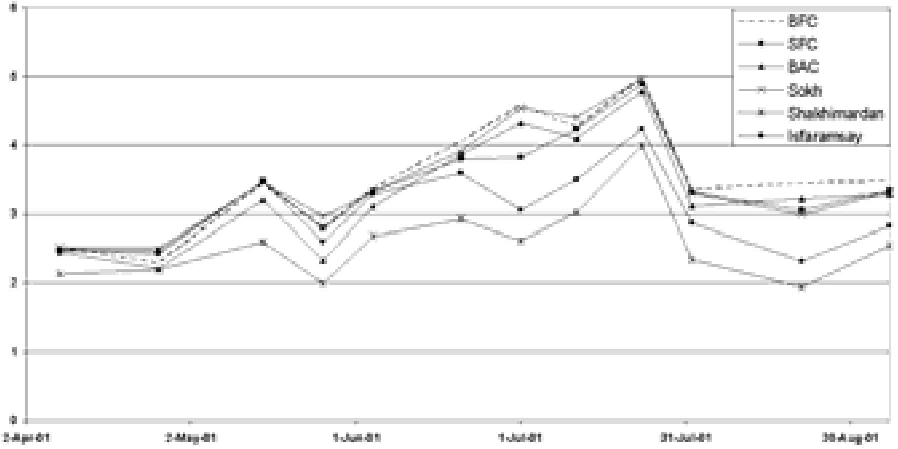


Figure 2: Mean ETa per irrigation system from AVHRR in Ferghana Province, Uzbekistan

The remotely sensed water consumed by crops can be combined to the crop yields of irrigation units. Such ratio is called the productivity of water consumed for a given crop and analyzed for ZID in Loeve et al. (2002). The scale effects shown in Figure 3 are for the irrigated rice sub-basin of ZID (Chemin, Alexandridis and Loeve, 2002) and for the irrigated cotton of Ferghana Province (Chemin et al., forthcoming).

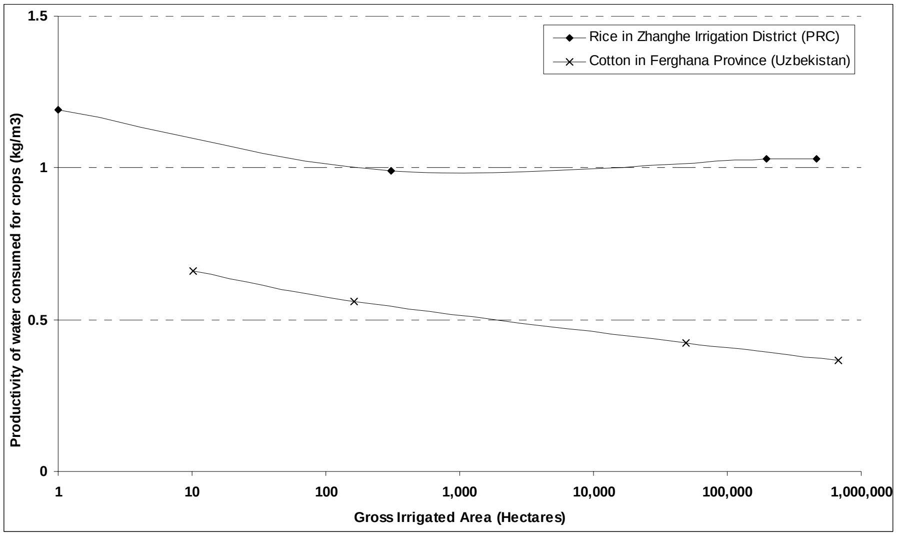


Figure 3: Scale changes of crop yield/crop ETs for a season in two systems in PRC and Uzbekistan

Accuracy elements

It is obviously not sensible to compare point-restricted information with area-wide data. Many issues are often raised on this subject but only highly sophisticated apparatus such as mentioned in Hemakumara et al. (2002) can address the comparison in very scientific experimental conditions. Nonetheless, limitations of various nature often bring research to find alternative best ways to give indications on the accuracy of the results.

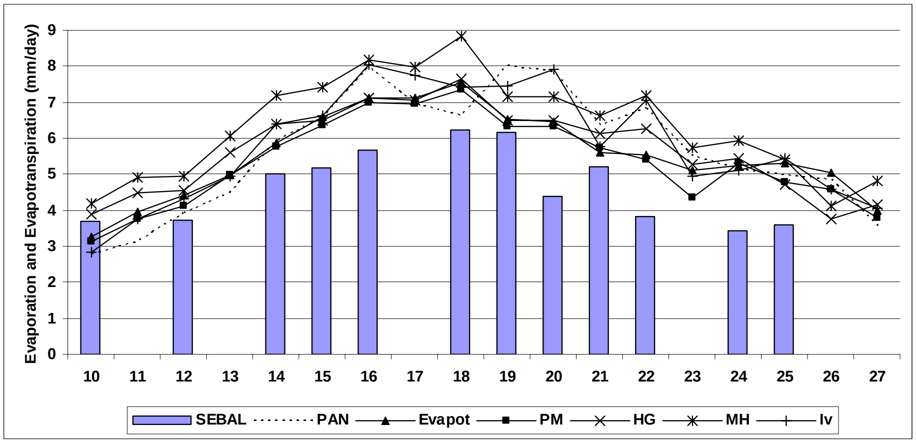


Figure 4: Decadal comparison of various E and ET references with ETa by remote sensing (in year 2001)

Notes: (In order of Figure 4) SEBAL = ET actual from remote sensing ; PAN = Pan evaporated water from Ferghana Meteorological station ; Evapot = simulated ETo with Evapot software (after Cholponkulov, 2002) ; PM = ETo Penman-Monteith (standard) ; HG = ETo Hargreaves (standard) ; MH = modified Hargreaves ; Iv = ETo Ivanov (standard).

Eventhough a comparison with various ET reference does not bring absolute sufficient elements for validation, it does contribute to a consistent cross-checking of the method of Actual ET calculation by remote sening. The information collected in Figure 4 is for the meteorological station of Ferghana (Chemin et al., 2002), the ETa from SEBAL has been collected on the large wetlands downstream of Besharyk. The absolute values of ET reference for Ferghana station on a decadal basis compared to the ETa variation gives an indication of the amount of confidence that can be given to the values of actual ET derived from the satellite remote sensing images. Typically ETo values are superior to the ETa values, as are confirmed by Figure 4, where the 1.1 Km^2 NOAA Pixel ETa is always having values below the ET reference by any method. The level of difference gives also an indication on the level of water stress that the environment is facing. ETa is real evapotranspiration, actually measured out of the all physical medium included in one pixel, may it be city, road, field or bare soil.

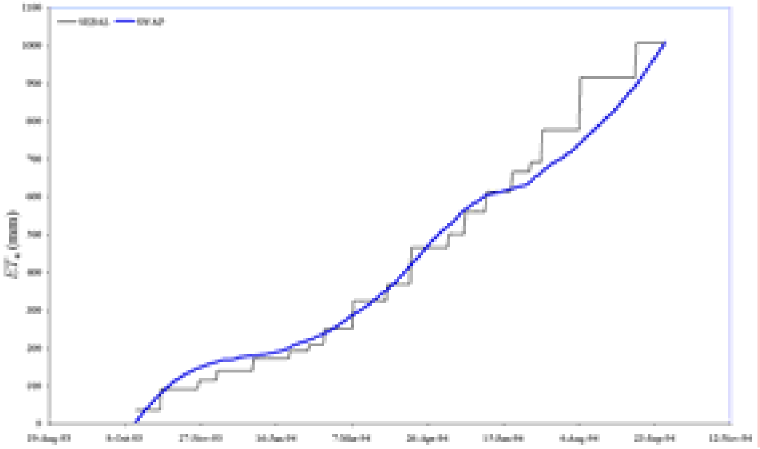


Figure 5: Cumulative actual evapotranspiration (ET_a) from the locally calibrated transient model SWAP and SEBAL for the Fourth Drainage Project near Faisalabad (after Bastiaanssen et al., 2002)

Bastiaanssen et al. (2002) have shown in their Pakistan study that no deviation of the annual actual evapotranspiration could be found at the field scale between the remote sensing and the transient model SWAP (Figure 5). They add that errors are there at small time scales, but the agreement with SWAP is overall good at larger time integrations. Also, the same authors mentioned that the Bowen ratio field measurement technique gave a difference of 10 % on the seasonal basis. Finally, the residual water balance of a 3 million hectares irrigation system showed a difference of 5 % in the same study.

Conclusion

The application of the energy-balance equation to satellite remote sensing has matured largely over the past decades, and can bring practical results already. Basic elements like temperature, Vegetation Indices and Albedo are already standard products that are used widely in the remote sensing science. They are also used to run through the setup of most of the energy-balance parameters. Surface roughness and $[T_{areo}\text{-}T_{rad}]$ are still under active research in order to limit the dependency on ground data. Wind speed is most likely to be always required as ground measurement.

Many irrigation systems in Asia have already been under investigation for ETa by remote sensing of the energy-balance with satisfactory levels. Actual developments are especially oriented towards more automatic processing of the models while keeping actual accuracy levels. Time series of ETa are now emerging as important combined temporal & spatial analysis tools for irrigated crops water consumption. Assessment of irrigated crops performance is largely benefiting from such advancements of the remote sensing science.

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LIST OF SYMBOLS AND ABBREVIATIONS

ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
C_p	Air specific heat at constant pressure
C_s	Soil surface air specific heat at constant pressure
dT	Soil to atmosphere temperature difference
E-Pan	Pan Evaporation
ET	Evapotranspiration
ETa	Actual Evapotranspiration
ETM	Enhanced Thematic Mapper
ETo	Reference Evapotranspiration
ETs	Seasonal Evapotranspiration
G_0	Soil Heat flux
H	Sensible Heat Flux
HG	Hargreaves
Iv	Ivanov
$K^{\downarrow}$	Incident Shortwave Radiation
$K^{\uparrow}$	Reflected Shortwave Radiation
$L^{\downarrow}$	Incident Longwave Raditation
$L^{\uparrow}$	Outgoing Longwave Radiation
LAI	Leaf Area Index
MH	Modified Hargreaves
MODIS	Moderate Resolution Imaging Spectroradiometer
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanographic and Atmospheric Administration
PBL	Planetary Boundary Layer
PM	Penman-Monteith
PRC	People’s Republic of China
r_{aH}	aerodynamic resistance for Heat Transport
Rn	Net Radiation
r_v	Aerodynamic surface resistance to vapor transport
r_s	Bulk surface resistance to evapotranspiration
RS	Remote sensing
SEBAL	Surface Energy Balance Algorithm for Land
SEBI	Surface Energy Balance Index
SVAT	Soil-Vegetation Atmosphere Transfer Models
SWAP	Soil Water Atmosphere Processes model
T_0	Land surface temperature
T_a	Air temperature
T_{aero}	Aerodynamic surface temperature

T_{rad}	Radiation surface temperature
T_s	Soil skin Temperature
TSEB	Two-Source Energy Balance algorithm
ZID	Zhanghe Irrigation District

β	Bowen Ratio
λ	Latent heat of vaporization
λE	Latent Heat Flux
ρ_{air}	Moist air density
ρ_{va}	Atmospheric vapor density
ρ_s	Soil surface air density
ρ_{vs}	Soil surface vapor density

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