Land surface temperature from remote sensing and from an energy water balance model for irrigation management

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Land surface temperature from remote sensing and from an energy water balance model for irrigation management

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Abstract. Soil Moisture is recognized as the key variable in the hydrologic water balance for operational purpose as for flash flood forecast system as well as for irrigation management. Respect to this role it is most of the time confined to an internal numerical model variable often without any control with measured data. This is mainly due to its intrinsic space and time variability and to the well known difficulties in assessing its value from remote sensing as from in situ measurements. The present paper investigates the possibility to control surface soil moisture trough the detection of land surface temperature from satellite remote sensing due to the simpler information and availability of infrared satellite images respect to the microwave ones. In this context the paper tries to asses soil moisture values and its spatial and temporal dynamic developing an energy water balance model (FEST-EWB) tested at field scale with fluxes measured from an eddy tower. Modelled soil moisture and temperature values are also compared with operative satellite data (MODIS) and in situ ground measurements.

Keywords. Irrigation – Land surface temperature – Energy water balance model – Energy balance closure**.**

La température de surface résultante de la télédétection et d'un modèle de bilan hydro-énergétique pour la gestion de l'eau

Résumé. *L'humidité du sol est reconnue comme étant la variable clé du bilan hydrologique à fins opérationnelles, comme la prévision des inondations et la gestion de l'irrigation. Vu ce rôle, elle est souvent présentée dans les modèles comme une variable numérique interne qui n'a aucun contrôle sur les données mesurées. Cela est principalement dû à sa variabilité intrinsèque dans l'espace et le temps, et aux difficultés d'évaluer sa valeur à l'aide de la télédétection et des mesures in situ. Cet article étudie la possibilité de contrôler l'humidité du sol à partir de la détection de la température de surface (LST) par télédétection satellitaire, vue la simplicité de l'information et la disponibilité des images satellitaires infrarouges ainsi que celles à micro-ondes. Dans ce contexte, l'article essaie d'évaluer l'humidité du sol et son dynamisme spatio-temporel en développant un modèle de bilan hydrique et énergétique (FEST-EWB) examiné à l'échelle du champ en mesurant les flux à partir d'un circuit de courant. Les valeurs simulées de l'humidité et de la température du sol sont également comparées aux données d'un satellite opératif (MODIS) et aux mesures effectuées in situ.*

Mots-clés. *Irrigation – Température de surface – Bilan hydrique et énergétique – Fermeture du bilan énergétique.*

I – Introduction

The water resources scarce availability in Mediterranean area, which occurs with an increasing frequency in the last years, requires an accurate irrigation water management, due to the fact that agriculture is the main water consumer. It becomes then important to monitor the irrigation performance evaluating the irrigation index, such as the irrigation water needs (IWN) which depends on evapotranspiration and soil moisture content. Soil Moisture is recognized as the key variable in the hydrologic water balance for operational purpose as for flash flood forecast system as well as for irrigation management (Albertson and Kiely, 2001; Montaldo and Albertson, 2003b). Respect to this role, it is most of the time confined to an internal numerical model variable (Dooge, 1986). This is mainly due to its intrinsic space and time variability and to the well known difficulties in assessing its value from remote sensing as from in situ measurements (De Troch *et al.*, 1994; Engman and Chauhan, 1995).

Land surface temperature (LST) is the parameter that links the energy fluxes between the atmosphere and the surface and so it becomes fundamental in the energy balance modeling to estimate the net radiation and the soil, sensible and latent heat fluxes (Noilhan and Planton, 1989; Famiglietti and Wood, 1994; Montaldo e Albertson, 2001). The availability of satellite remote sensing information makes easy to retrieve LST in raster format, mainly suited for the use in conjunction to distributed model. However, some uncertainties have to be addressed, such as the definition of satellite LST over an heterogeneous area that is a function of the surface temperature of each component of the area (bare soil or vegetation), of the occupied percentage by each type of soil and of the scan angle of view of the satellite (Norman *et al.*, 1995; Kustas *et al.*, 2004; Jacob *et al.*, 2004; Soria and Sobrino, 2007).

The potentiality of a “representative surface temperature” in an energy mass balance model as a tool to monitor soil moisture dynamic from operative satellites such as TERRA with on board MODIS sensor is discussed.

At field scale, the paper tries to asses soil moisture values and its spatial and temporal dynamic developing an energy water balance model (FEST-EWB) tested at field scale with fluxes measured from an eddy tower. Modelled soil moisture and temperature values are also compared with operative satellite data (MODIS) and in situ ground measurements to improve irrigation management for the year 2006 in the Landriano agricultural test area.

The goodness of the measured ground data is evaluated testing the energy budget closure considering the additional terms of the energy storage such as the photosynthesis flux, the crop and air enthalpy changes and the soil surface layer heat storage. In fact the traditional energy budget is typically not closed when measuring energy with an eddy correlation station and the available energy is usually bigger than the sum of the turbulent vertical fluxes with a ratio that ranges between 70 and 90% (Jacobs *et al.*, 2008; Meyers and Hollinger, 2004). This is mainly due to instrumental errors, especially those of the eddy covariance technique, to the problem of heterogeneities in the area and to the energy storage.

II – The energy balance model

FEST-EWB is a distributed hydrological energy water balance model and it is developed starting from the FEST-WB and the event based models FEST98 and FEST04 (Mancini, 1990; Rabuffetti *et al.*, 2008). FEST-WB computes the main processes of the hydrological cycle: evapotranspiration, infiltration, surface runoff, flow routing, subsurface flow and snow dynamic. In the FEST-EWB the energy balance module is introduced where land surface temperature is the key parameter that links the energy fluxes between the low atmosphere and the ground surface.

At the ground surface, the complete energy balance equation is expressed as:

$$Rn - G - (Hs + Hc) - (LEs + LEc) = \frac{\Delta W}{\Delta t}$$

where: Rn (Wm^{-2}) is the net radiation, G (Wm^{-2}) is the soil heat flux, H_s and H_c (Wm^{-2}) and LE_s and LE_c (Wm^{-2}) are respectively the sensible heat and latent heat fluxes for bare soil (s) and for canopy (c), and $\Delta W/\Delta t$ (Wm^{-2}) assembles the energy storage terms. These terms are often negligible, especially at basin scale with a low spatial resolution; instead at local scale the contribution of these terms could be significant (Jacobs *et al.*, 2008; Meyers and Hollinger, 2004).

All the terms of the energy balance depend on the land surface temperature (LST) and so the energy balance equation can be solved with the well known Newton-Rhapson method:

$$LST_n = LST_{n-1} + \frac{f_t(LST_{n-1})}{f_t'(LST_{n-1})}$$

where LST_n is the actual value, LST_{n-1} is the value at the previous iteration, $f_t(LST_{n-1})$ is the energy balance function and $f_t'(LST_{n-1})$ is its derivative. The solution is acceptable when:

$\left|\frac{f_t(LST)}{f_t'(LST)}\right| < tolerance$ and $f_t(LST) < tolerance$, with tolerance equal to 0.001.

The terms of the energy balance equation are described in the following.

The net radiation is the algebraic sum of the incoming and outgoing short wave and long wave radiation:

$$R_n = R_s(1-r) + \xi_c \sigma (T_a^4) - \xi_s \sigma (LST^4)$$

where R_s is the incoming short wave radiation (Wm^{-2}), while the outgoing short wave radiation (Wm^{-2}) is a fraction of R_s with the albedo (r). ξ_s is the soil emissivity, σ is the Stefan-Boltzmann constant ($Wm^{-2}K^{-4}$) and LST and Ta are respectively the land surface and the air temperature (K). In literature several different equations exist for the description of the atmosphere emissivity, ξ_c, considering clear and cloudy skies with different cloud cover fraction. For this study an average value of the measured atmosphere emissivity is used.

The soil heat flux is the heat changed for conduction with the sub-surface soil and it is evaluated as:

$$G = \left(gterm / dz \right)(LST - T_0)$$

where T_0 is the temperature below the first layer of soil (K) and dz is the soil thickness (m). gterm is the soil thermal conductivity ($Wm^{-1}K^{-1}$) which depends on the soil water tension valuated with the McCumber – Pielke equation (McCumber and Pielke, 1981; Peters – Lidard *et al.*, 1998).

The sensible heat flux is considered for the situations of bare soil, H_s, and of canopy presence, H_c. The cell of the computational domain is characterized by a vegetation fraction, f_v, to discriminate the percentage of vegetation coverage. The equation of this vertical flux is:

$$Hs + Hc = (1 - fv)\frac{\rho_a c_p}{r_a}(LST - T_a) + fv\frac{\rho_a c_p}{r_a}(LST - T_a)$$

where ρ_a is the air density (Kgm^{-3}), c_p is the specific heat of humid air ($MJkg^{-1}K^{-1}$) and r_a is the aerodynamic resistance (sm^{-1}) which determines the transfer of heat and water vapour from the evapotranspirating surface into the air above the canopy. Correction functions for atmospheric stability or instability are included using the Thom model (Thom, 1975):

$$r_a = \frac{\left[\ln\left(\frac{z_m - d}{z_{om}}\right) - \Psi_m\left(\frac{z_m - d}{L}\right)\right]\left[\ln\left(\frac{z_h - d}{z_{oh}}\right) - \Psi_h\left(\frac{z_h - d}{L}\right)\right]}{k^2 u_z}$$

where z_m is the height of wind measurements (m), z_h is the height of humidity measurements (m), d is the zero plane displacement height (m), z_{om} is the roughness length governing momentum transfer (m), z_{oh} is the roughness length governing transfer of heat and vapour (m), k is the Von Karman's constant, 0.41, and u_z is the wind speed at height z (ms^{-1}). Ψm and Ψh are the correction functions for the heat transfer and the momentum exchange with different equations in case of atmospheric stability (Panofsky and Dutton 1984) and of unstable conditions (Paulson, 1970). L is the Monin-Obukhov length (m).

The latent heat fluxes for bare so\il, LE_s, and of canopy, LE_c. are:

$$LEc + LEs = f_v\left(\frac{\rho_a c_p}{\gamma (r_a + r_c)}\right)\left(e^* - e_a\right) + (1 - f_v)\frac{\rho_a c_p}{\gamma (r_a + r_s)}\left(e^* - e_a\right)$$

where γ is psychrometric constant (Pa°C^{-1}), e*is the saturation vapour pressure (Pa) computed as function of the LST and e_a is the vapour pressure (Pa).

The canopy resistance, r_c (sm^{-1}), which describes the resistance of vapour flow through the transpiring crop, is expressed as (Jarvis,1976):

$$r_c = \frac{r_{s\,\min}}{LAI}\frac{(FC - WP)}{(SM - WP)}$$

considering $r_{s\,min}$ as the minimum stomatal resistance (sm^{-1}), LAI the leaf area index, FC the field capacity, WP the wilting point and SM the soil moisture.

The soil resistance, r_S (sm^{-1}), is the resistance at the evaporating soil surface (Sun,1982):

$$r_s = 3.5\left(\frac{SM_{sat}}{SM}\right)^{2.3} + 33.5$$

where SM_{sat} is the soil moisture at saturation.

The latent heat of vaporization, λ ($MJKg^{-1}$), and the water density, ρ_w (Kgm^{-3}), link the latent heat flux with the evapotranspiration, ET (ms^{-1}):

$$LE = \lambda\, \rho_w ET$$

The photosynthesis flux (F_CO_2), the crop and air enthalpy changes (S_{canopy} and S_{air}) and the soil surface layer heat flux (S_{soil}) are additional fluxes term (Wm^{-2}) considered in the energy balance:

$$\frac{\Delta W}{\Delta t} = F\_CO_2 + S_{canopy} + S_{air} + S_{soil}$$

The photosynthesis flux, that is the change in the Gibbs free energy, is calculated with the conversion from the measured flux of 1 mg CO_2 m^{-2} s^{-1} to 11 Wm^{-2} (Nobel, 1974).

The air enthalpy is evaluated as:

$$S_{air} = \frac{\Delta T_a \rho_a c_p}{\Delta t}\Delta z_{air}$$

where ΔT_a is the difference of air temperature (°C), Δt is the time step (s) and Δz_{air} is the height of the measurement instrument (m).

The canopy enthalpy is computed only over a fixed vegetation height:

$$S_{canopy} = \frac{\Delta LST\,(m_w c_w + m_b c_b)}{\Delta t}$$

where m_w and m_b (Kgm^{-2}) are respectively the masses of water and biomass, c_w and c_b ($JKg^{-1}K^{-1}$) are the specific heat capacities of water and biomass.

A similar approach is used for the heat flux in the soil surface layer:

$$S_{soil} = \frac{\Delta T_{soil}\,(SM m_w c_w + \rho_s c_s)}{\Delta t}\Delta z_{soil}$$

where T_{soil} is the soil temperature (K) at the soil heat flux plate depth (Δz_{soil}), ρ_s (Kgm^{-3}) is the soil density and c_s ($JKg^{-1}K^{-1}$) is the specific heat of soil capacity.

III – The energy budget measurement

Data used in this analysis were collected during the year 2006 from 13th of March to 11th of October with a micrometeorological station located in an experimental field of maize in Landriano in the Po river plain (Northern Italy) operated by the Politecnico of Milano. The station is equipped with: a 4-component radiometer, a gas analyzer coupled to a 3D sonic anemometer necessary for the eddy correlation technique for the estimation of the latent heat flux, several soil moistures probes, one rain gauge, heat flux plates, soil temperature probes for the soil heat flux, a PAR sensor, an infrared sensor temperature and tensiometers. The station acquires data averaged on half an hour basis, 24 hours a day (Horeschi *et al.*, 2008). The raw data show the closure of the energy balance. Improvement in energy balance closure can be achieved considering additional fluxes such as the photosynthesis flux, the enthalpy changes of crop and air and the soil surface layer heat flux (Meyers and Hollinger, 2004) (Figure 1).

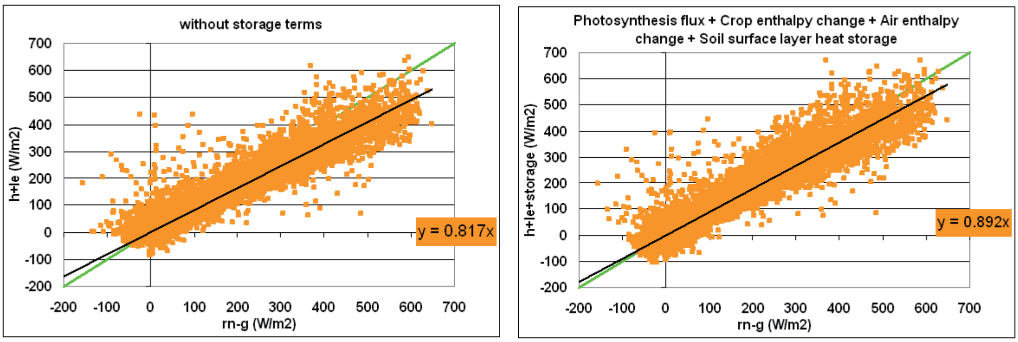

Figure 1. Energy budget closure for measured fluxes (left) and considering the additional flux measurements (right).

IV – Model validation with ground and satellite data

1. Energy fluxes

The measured and simulated principal fluxes of the energy budget, such as the net radiation, the latent and sensible heat fluxes and the soil heat flux, are compared (Figure 2.) and a good accuracy is reached.

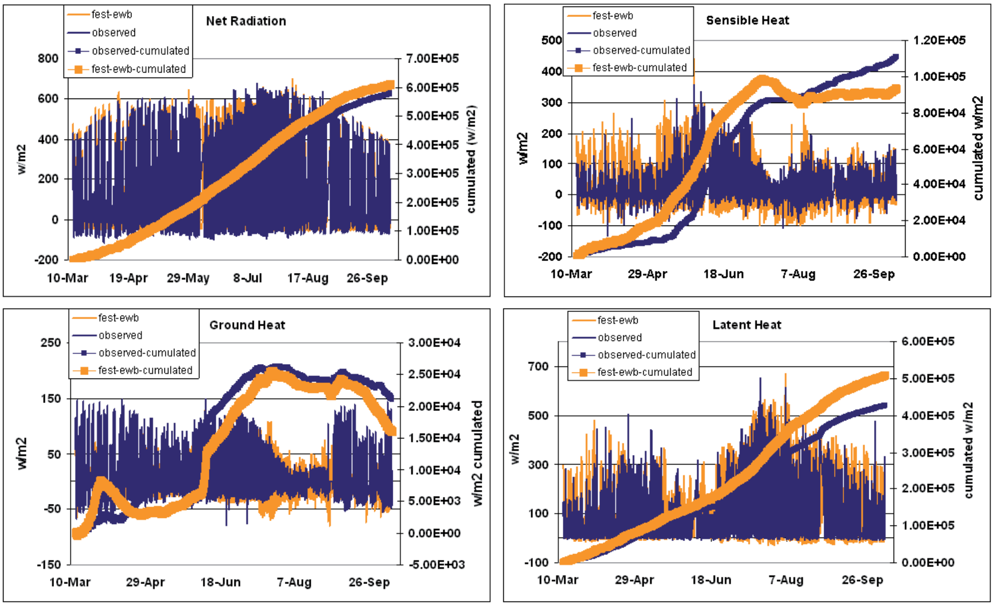

Figure 2. The comparison of the simulated and measured energy fluxes.

These results are confirmed from a statistical analysis looking for the minimization of the root mean square error (RMSE) and the maximization of the efficiency of the Nash and Sutcliffe index (Nash and Sutcliffe, 1970). The RMSE has low values for each flux in regard to its maximum value (Table 1).

Table 1. RMSE and the Nash and Sutcliffe index for the energy fluxes.

	η	RMSE (Wm^{-2})
Net Radiation	0.80	88.83
Latent Heat	0.61	68.88
Sensible Heat	0.35	44.15
Ground Heat	0.51	27.82

2. Land surface temperature

As said before land surface temperature is the key parameter that links the energy fluxes between atmosphere and surface in the energy balance modelling. Satellite images are an important instrument for the use in conjunction to distributed model, even if some uncertainties have to be addressed, such as the definition of satellite LST of an heterogeneous area. For this study we use the LST product from MODIS radiometer (satellite TERRA, http://ladsweb.nascom.nasa.gov/index.html) and in particular 104 daily and nocturne satellite images for the simulation period from 13th of March to 11th of October 2006.

LST from MODIS and LST measured from the radiometer of the eddy station are compared with the land surface temperature simulated from FEST-EWB. From Figure 3, the linear regression forced through the origin for the LST from FEST-EWB against LST form the station is y=0.95x, showing a good behaviour of the model in representing the observed data. When the modelled values are compared with the satellite ones, a slope of 0.89 is reached. Also the rout mean square error (RMSE) and the Nash and Sutcliffe index (η) confirm the results of the modelling simulation according to the ground measured data and to the LST retrieved from MODIS images with high values of the Nash - Sutcliffe index and low values of the RMSE (Table 2).

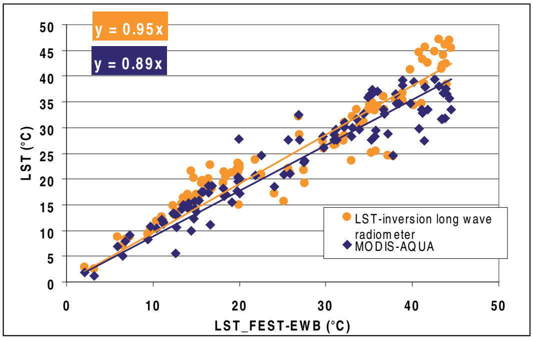

Figure 3. Comparison among land surface temperature simulated and measured from the station and from MODIS (left). RMSE and the Nash and Sutcliffe index for land surface temperature (right).

Table 2. RMSE and the Nash and Sutcliffe index for land surface temperature.

	η	RMSE (°C)
MODIS-AQUA	0.83	4.96
LST-station	0.89	3.99

V – Modelling results and irrigation practice

Soil Moisture from modelling results (FEST-EWB), satellite and in situ data land surface temperature are compared, for the Landriano agricultural field (9 ha) cultivated with maize. Soil moisture field data are acquired using a TDR sensor (5 cm) after each irrigation in 37 points, while local vertical profile is detected continuously in time at the station (Horeschi, 2008). The field is irrigated with farrow irrigation that causes a non homogeneous spatial variability (Figure 4). The FEST-EWB model seems to well reproduce the spatial variability of soil moisture considering both precipitation and irrigation (Figure 4).

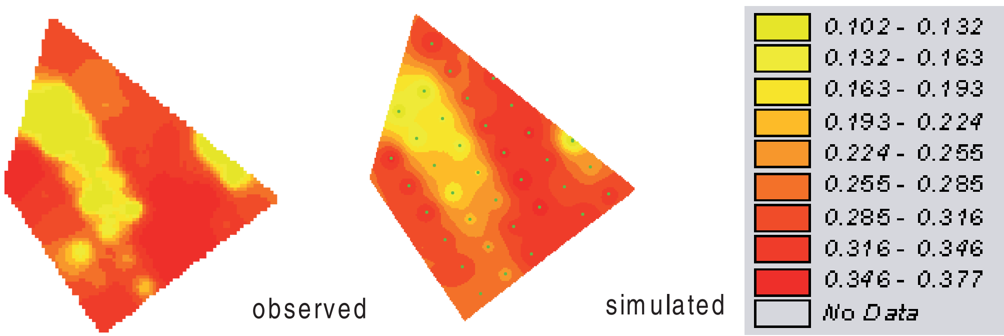

Figure 4. The distributed soil moisture measurement campaign of 6th August 2006 and its simulation.

The soil moisture behaviour of observed and of simulated values is consistent with simulated LST and latent heat flux. As we can observe from the following figure the warmer areas in the middle of the field are the areas with the lower soil moisture content and with the lower change of latent heat flux (Figure 5).

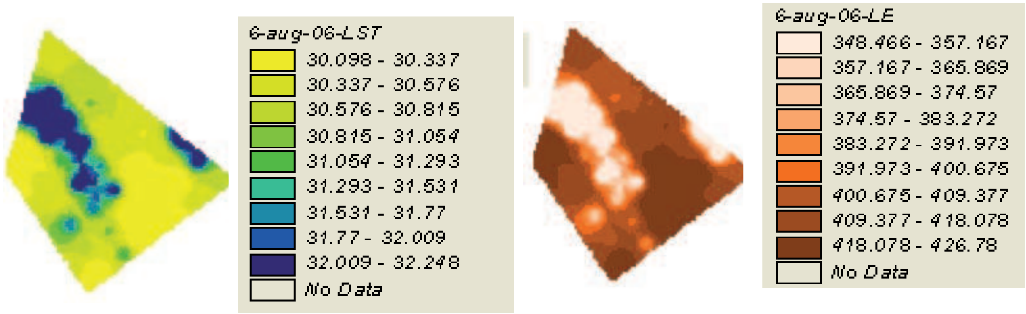

Figure 5. The distributed modeled LST (K) and LE (Wm^{-2}) after the irrigation event of 6th August 2006.

The FEST-EWB model seems to well reproduce also soil moisture temporal dynamic at the station considering both precipitation and irrigation (Figure 6).

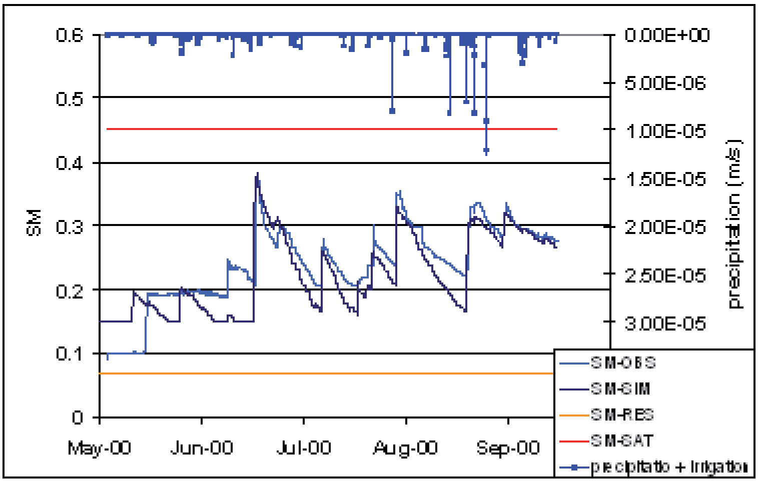

Figure 6. Simulated and observed soil moisture temporal dynamics.

Here in, we present a preliminary result of an agricultural application of the FEST-EWB model oriented to improve and to monitor the irrigation water needs (IWN) for different types of crops. As well known, the IWN (FAO, 1986; D'Antonio *et al.*, 2008) is actually computed as a difference between the potential evapotranspiration (ETP) and the rainfall, as precipitation plus irrigation (Figure 7). So a positive value of the index shows water deficit, while a negative value shows excess of water. In Figure 7, the irrigation water needs index is reported for the entire vegetation period from 29th May to 8th September, as the net rainfall. Negative values of the IWN index are present during two irrigation, respectively 13th -14th July and 20th – 21st July, and also during an heavy precipitation event of 25th August, showing excess of water.

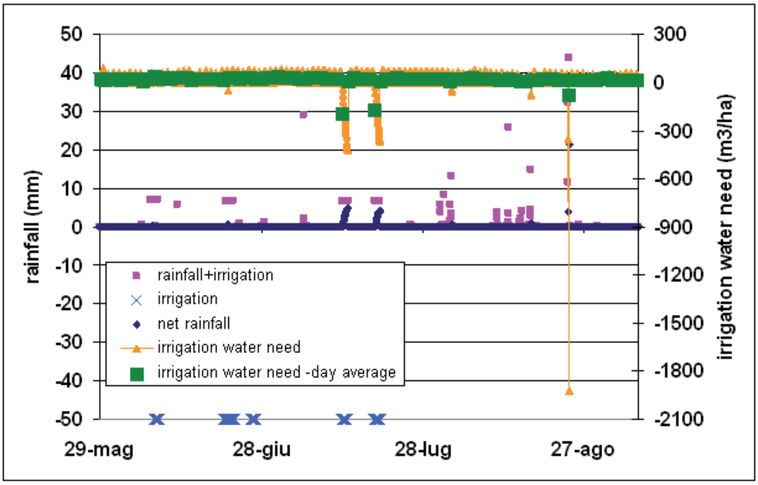

Figure 7. The irrigation water index (FAO, 1986) at hourly and daily time interval plus irrigation an rainfall.

A modified water deficit index is presented as a difference between the potential evapotranspiration and the effective one (Figure 8). The vegetation period can be clearly separated into two sub periods, divided by the irrigation event of 13th -14th July. In the first sub period, the water deficit is very high; while, when the irrigation is performed, this difference becomes very small due to the fact that the maize plant almost reached its transpiration potential. Therefore the two irrigations of 13th -14th July and of 20th – 21st July, even though necessary, seem to have been excessive causing an excess of water.

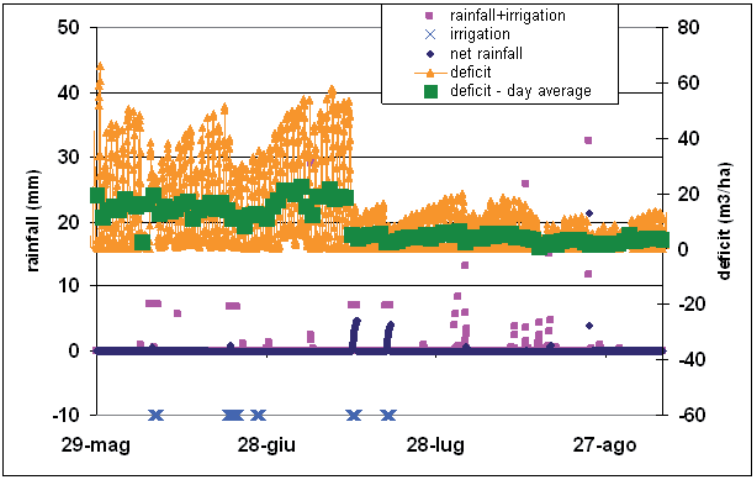

Figure 8. The modified water deficit index at different time scale together wit rainfall and irrigation.

VI – Conclusion

The present paper investigated the possibility to control surface soil moisture into a distributed hydrologic model trough the detection of land surface temperature from satellite remote sensing due to the simpler information and availability of infrared satellite images respect to the microwave ones. The energy water balance model (FEST-EWB) reproduces soil moisture values and its spatial and temporal dynamic in agreement with observed data. Modelled soil moisture and land surface temperature values are also compared with operative satellite data (MODIS) and with in situ ground measurements.

The goodness of the measured ground data has been evaluated testing the energy budget closure considering the additional terms of the energy balance such as the photosynthesis flux, the crop and air enthalpy changes and the soil surface layer heat flux. These terms allow an improvement in the energy budget closure of 7.5 %, that it is not negligible even if the single component gives a low contribution. FEST-EWB is developed considering these additional terms and the energy fluxes from field data and modelling are in good agreement.

A preliminary study is made for the irrigation practice considering the irrigation water need index and the water deficit index, showing possibility of a more parsimonious use of water for maize field.

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