Water and Energy Fluxes in a Riparian Wetland

O. Batelaan[a], L. Q. Hung[a] and B. Verbeiren[a]

[a] Department of Hydrology and Hydraulic Engineering, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium, email: batelaan@vub.ac.be

ABSTRACT

Monitoring of water and energy fluxes is a requirement for assessment of climate and anthropogenic effects on natural and agricultural ecosystems [1]. These fluxes consist of the physical transfers between soil, vegetation and atmosphere. In order to describe these transfers, on local, regional or global scale, and the changes taking place in the compartments it is necessary to have measurements and models to estimate these fluxes. Distributed hydrological models are appropriate tools and are constantly improving the understanding of this cycling of water through soils, vegetation and atmosphere. Also for the relatively new emerging field of ecohydrology estimation of spatially distributed water and energy levels is essential for predicting occurrence of vegetation species under site specific conditions. Since evapotranspiration is a major component of all combined fluxes it deserves to receive the necessary attention. For the estimation of remotely sensed evapotranspiration, the most popular approach is to use surface temperature and vegetation indices at small scale and low resolution satellite imagery to estimate regional fluxes. New developments in thermal airborne (ATM) combining with CASI imagery allow deriving hydrological relevant observations at a resolution of 1-10 m. In this research we propose to estimate on basis of thermal ATM imagery evapotranspiration and other elements of the water and energy balance on a scale, which allows discriminating local wetness and vegetation heterogeneity in relation to differences in soil and vegetation condition. The evapotranspiration in the study area is simulated with the Surface Energy Balance Algorithm for Land (SEBAL) [2]. The daily total evapotranspiration is calculated for the complete study area, but special attention is given to a grassland area for which detailed soil moisture measured conditions have been obtained. The estimated evapotranspiration values can be related to other hydrological and vegetation conditions, resulting in an increased understanding of the ecohydrological functioning of the study area.

Keywords: ATM, hyperspectral, evapotranspiration, SEBAL model, wetland, Belgium.

1 INTRODUCTION

The estimation of water balances at different spatial and temporal scales is a fundamental task of the hydrological science. In recent years physically based distributed models are more and more used for this task. These models simulate water and energy fluxes between soil, vegetation and atmosphere, their applications range from modeling climate change on global scale to ecohydrological modeling on local scale. Characteristic is that they require spatially distributed data and that the evapotranspiration is general the biggest flux to be simulated.

The Surface Energy Balance Algorithm for Land (SEBAL) [2] model is an image-processing and GIS model comprised of 25 computational steps that calculate the actual (ET_{act}) and potential evapotranspiration rates (ET_{pot}) through the balance of sun energy on the earth surface. SEBAL has been so far mainly been applied on regional scale on the basis of NOAA-AVHRR imagery. The key input data for SEBAL consists of spectral radiance in the visible, near-infrared and thermal infrared part of the spectrum. SEBAL computes a complete radiation and energy balance along with the resistances for momentum, heat and water vapour transport. The resistances are a function of state conditions such as soil water potential, wind speed and air temperature and change from day-to-day.

In this paper we test the applicability of the SEBAL methodology for estimation of evapotranspiration fluxes with spatially high resolution hyperspectral imagery (CASI) and thermal data from the ATM sensor.

2 SURFACE ENERGY BALANCE ALGORITHM FOR LAND

The primary basis for the SEBAL model is the surface energy balance (Fig. 1). The instantaneous ET_{act} flux is calculated for each pixel of the image as a ‘residual’ of the surface energy budget equation

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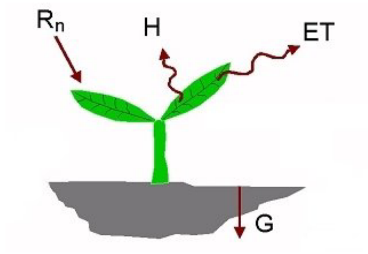

Figure 1. Surface energy balance [2].

$$ET=R_n\text{-}G\text{-}H \tag{1}$$

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]. 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 (Fig. 2). This is specified in the surface radiation balance equation,

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

where $R_{S\downarrow}$ is the incoming short-wave radiation [W/m^2], α is the surface albedo [-], $R_{L\downarrow}$ is the incoming long wave radiation [W/m^2], $R_{L\uparrow}$ is the outgoing long wave radiation [W/m^2], and ε_o is the surface thermal emissivity [-].

In Eq. (2) the amount of net short-wave radiation ($R_{S\downarrow}$ - $\alpha R_{S\downarrow}$) that remains available at the surface is a function of the surface albedo (α). The broadband surface albedo α is derived from the narrow band spectral reflectances $\alpha(\lambda)$ measured by each satellite band. The incoming short-wave radiation ($R_{S\downarrow}$) is computed using the solar constant, the solar incidence angle, the relative earth-sun distance and a computed broadband atmospheric transmissivity. This latter transmissivity can be estimated from sunshine duration or inferred from pyranometer measurements (if available). The incoming long wave radiation ($R_{L\downarrow}$) 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 ($R_{L\uparrow}$) is computed using the Stefan-Boltzmann equation with a calculated surface emissivity and surface temperature. Surface temperatures are derived 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 (R_n) to compute the "residual" energy available for evapotranspiration (λE). Soil heat flux is empirically calculated as a G/R_n 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 ($\lambda E\approx0$) and wet ($H\approx0$) 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 into daily λE_{24} values by holding the evaporative fraction constant. The evaporative fraction, EF [-], is:

$$EF = \lambda E/ (R_n - G) \tag{3}$$

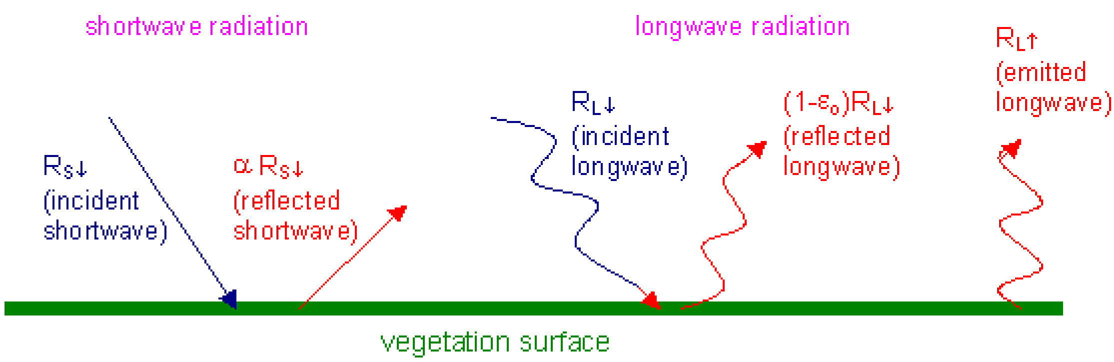

Figure 2. Surface radiation balance [2].

Field measurements under various environmental circumstances have indicated that EF behaves temporally stable during the diurnal cycle. Since EF ≈ EF_{24}, i.e. the 24 hour latent heat flux, λE_{24} [W/m^2], can be determined as:

$$\lambda E_{24} = EF\ Rn_{24} \quad (4)$$

For simplicity, the 24-hour value of G is ignored in Eq. (4). The second step is the inversion of the Penman-Monteith equation (5) for the estimation of the surface resistance, r_s [s/m]. The surface resistance is the most important factor between the soil moisture condition in the unsaturated zone and the evapotranspiration to the atmosphere [3].

$$\lambda E_{24} = (s_a\ Rn_{24} + \rho_a c_p\ \Delta e/r_a) / (s_a + \gamma\ (1 + r_s/r_a)) \quad (5)$$

Where s_a [mbar/K] is the slope of the saturated vapour pressure curve, $\rho_a c_p$ [J/m^3 K] is the air heat capacity, Δe [mbar] is the vapour pressure deficit, r_a [s/m] is the aerodynamic resistance and γ [mbar/K] is the psychrometric constant. The parameters s_a, Δe and r_a are controlled by meteorological conditions, and R_n and r_s by the hydrological conditions. Since the SEBAL computations can only be executed for cloudless days, the result of λE_{24} from Eq. (4) has been used to invert the Penman-Monteith equation (5) and to quantify spatial distribution of r_s. The r_s map so achieved, will consequently be used to compute λE_{24} by means of Eq. (5) for all days without satellite imagery available [3]. The total ET_{act} for any given period can now be derived by adding up the daily λE_{24} estimates.

3 DATA AND STUDY AREA

The Department of Hydrology and Hydraulic Engineering of the Vrije Universiteit Brussel (VUB) participated in the airborne hyperspectral remote sensing campaign, CASI-ATM 2003, executed by the Flemish Institute for Technological Research (VITO), operated on behalf of the Belgian Science Policy Office. For this hyperspectral campaign a combination of two sensors, on board of Dornier 228 aircraft, was used: the Compact Airborne Spectrographic Imager (CASI-2) and the ATM sensor. The CASI-2 sensor collects data in approximately 96 contiguous spectral bands, covering a wavelength range of 400 to 910 nm.

On June 16, 2003, the hyperspectral CASI-ATM dataset was acquired, at around 12am, in 3 North-South oriented flight lines, covering the total study area. At the same time of flight, ground measurements like air temperature, vegetation height, soil and surface temperatures were obtained. Vito provided radiometrically calibrated, geometrically and atmospherically corrected imagery. During the flight spectral characteristics of eight vegetation targets were measured with a handheld spectroradiometer (ASD Fieldspec Pro FR), as well as sun photometer measurements (Microtops II), to obtain the necessary information to atmospherically correct the images with ATCOR4. The image is projected as Lambert Conformal Conic (LCC) – 1972. Figure 3 shows the measurements of one of the vegetation targets in the selected grass field.

As a preliminary step towards reducing the errors of the data to be analyzed, the imagery was visually inspected and noise dominated bands were removed (0.856-0.971 µm). The resulting image file for all subsequent analyses of the study area was therefore reduced from 96 to 79 useable bands. The ATM (10.750 µm) image is of very good quality. Further applied corrections are the Empirical Flat Field Optimal Reflectance Transformation (EFFORT)

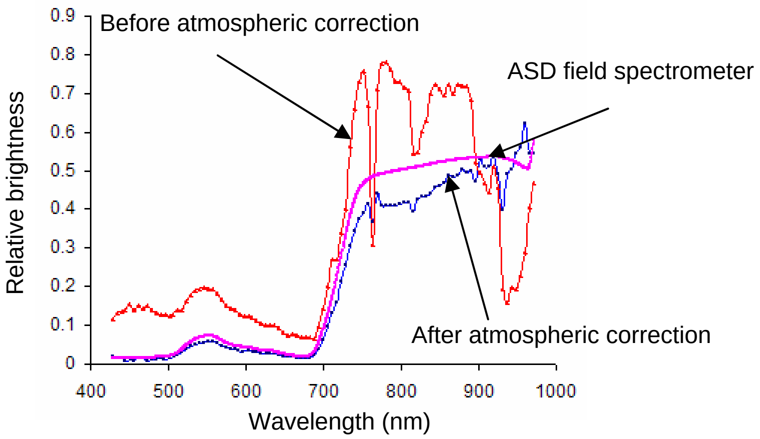

Figure 3. Spectral curve of selected grass target before and after atmospheric correction compared to ASD field reference spectral curve.

and the MNF transformation (forward and invert). The final corrected CASI-ATM image has a resolution of 2.44 m.

The Doode Bemde wetland is located east of Brussels, 8 Km south of Leuven, within the valley of the Dijle River. This area has been a subject of detailed ecohydrological studies [4] (Fig. 4). The soil textures in the Doode Bemde area are sandy loam (42%) and silt (58 %), respectively in the northeastern and western part. The land cover consists of deciduous forest (25 %), mixed forest (19 %), agriculture (13 %), maize (11%), and meadow (10 %). The aquifers in the area belong to the Brussels Formation (Eocene). The slopes vary from 0 to 34 %, with a mean value of 3 %. The precipitation and open water potential evaporation have respectively a mean value of 370 and 116 mm during winter and 390 and 554 mm during summer. In this study, the small grass area (Fig. 4) is chosen as a target to estimate the daily total evapotranspiration (ET_{24}) based on the SEBAL methodology.

4 RESULTS

The CASI-ATM images were processed by the GIS ILWIS 3.2 and AHAS 1.3 for application of the SEBAL methodology. In ILWIS/AHAS the necessary intermediate maps such as NDVI, SAVI, LAI, instantaneous net radiation, soil heat flux, sensible heat flux, latent heat flux, evaporative fraction and finally a total daily evapotranspiration were calculated. The surface temperature map was extracted from the ATM image assuming an

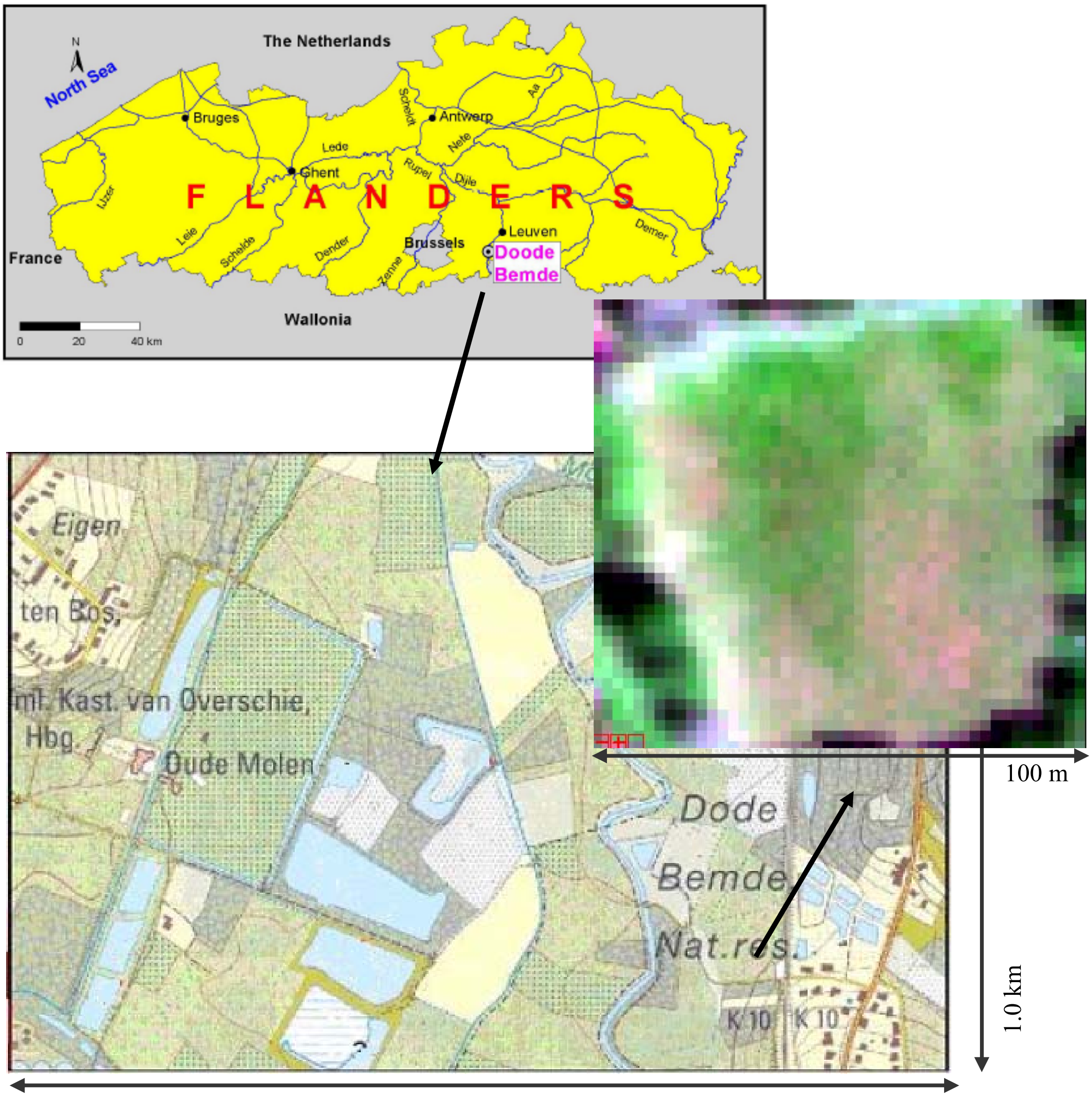

Figure 4. Study area, with grass field for which evapotranspiration flux was determined.

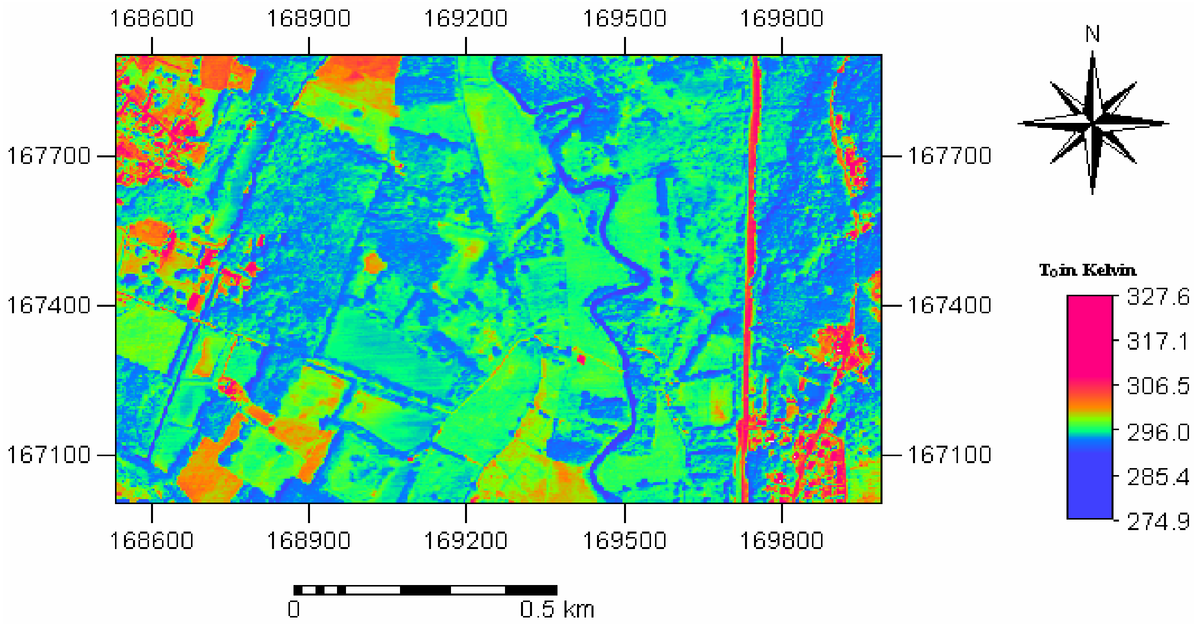

Figure 5. Surface temperature map in Kelvin for Doode Bemde.

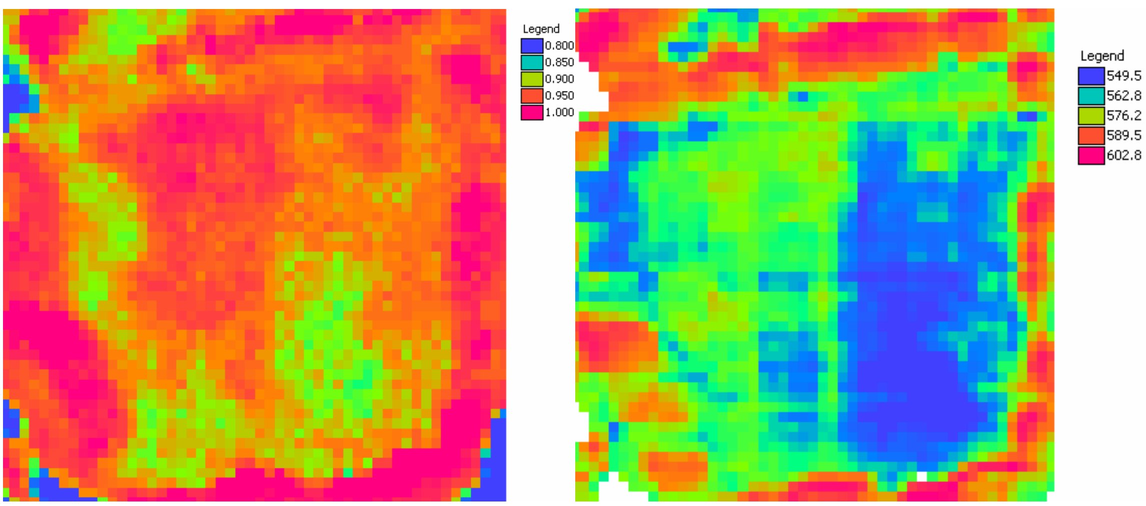

Figure 6a (left). Normalized vegetation difference index (red=682 nm, nir=757 nm). **6b (right)** Instantaneous net radiation in Watt.m^{-2}. Both for grass field in Doode Bemde wetland.

emissivity of 0.96. In Fig. 5 the range of surface temperature is 274.9º to 327.6º K. The temperature is correlated with the type of surface cover, low temperatures are related with water bodies, somewhat higher values correspond to areas with dense vegetation and relatively high temperatures occur in areas with low vegetation density. The highest values of surface temperature are found in the man-made areas.

As an indication of the evaporative fluxes in the about 100 by 100m sized grass field in the SE corner of the Doode Bemde wetland, Fig. 6a shows the NDVI map, Fig. 6b the instantaneous net radiation and Fig, 7a the latent heat flux. The value of the latent heat flux depends on the estimated net radiation and the much smaller soil and sensible heat flux. It ranges between 450 to 620 Watt.m^{-2} with the low values corresponding to low density vegetation areas (dry) and the highest values corresponding to the denser grass parts (wet) on the west side of the area.

5 DISCUSSION AND CONCLUSIONS

Hyperspectral remote sensing and GIS tools were successfully applied in the estimation of evapotranspiration of the Doode Bemde wetland, Belgium. The data used in this study includes hyperspectral imagery from the CASI-ATM

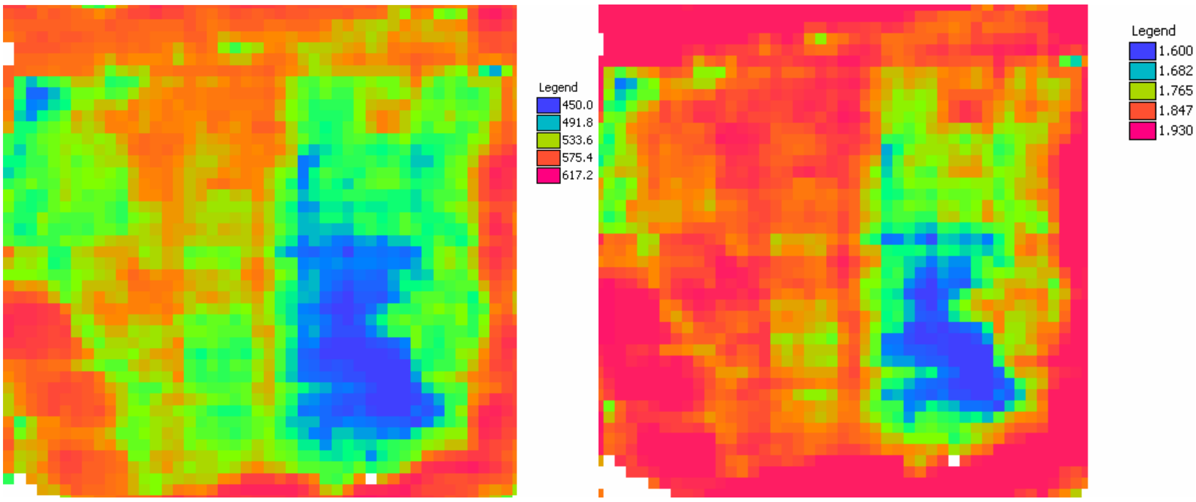

Figure 7a (left). Latent heat flux in Watt.m^{-2}. **7b (right)** Actual daily evapotranspiration in mm/day. Both for grass field in Doode Bemde wetland.

sensor and ground measurements like air, surface and soil temperatures and vegetation height. The hyperspectral images were calibrated using ENVI package and further processed by ILWIS 3.2 and AHAS 1.3 packages. The evapotranspiration is estimated using Surface Energy Balance Algorithm for Land (SEBAL) model. Solar radiation, soil, sensible and latent heat flux as parameters of the SEBAL model were prepared from the hyperspectral data and the ground meteorological data like humidity, air temperature, air pressure, etc. With the support of the ATM image and detailed climatic, vegetation, and topographic information, it is shown that SEBAL model can be applied successfully for high spatial and spectral resolution imagery, although so far it was mainly applied to low resolution NOAA-AVHRR imagery.

The evapotranspiration in the grass field area ranges from 1.6 to 2.0 mm/day (Fig. 7b). This seems to be a relatively low estimate compared to evapotranspiration estimates based on the Penman-Monteith method (~3.5 mm/day) for the whole area (Doode Bemde). However, because the grass field area is enclosed by dense and high trees, the wind velocity is relatively small, which reduces the turbulent upward transport of the latent heat. Additionally the soil moisture content is also lower than in many other parts of the wetland areas in Doode Bemde due to the fact that the grass field is located on the foot of the valley flank, which gives it a clear gradient in soil moisture content [5]. This results in relatively higher evapotranspiration fluxes in the lower compared to the higher (upslope) parts.

Evapotranspiration varies, as from this study appears, considerably over short distances in dependence of a complex set of landscape, ecological and hydrometeorological factors. High spatially resolution distributed evapotranspiration knowledge is therefore essential in estimating surface and groundwater balances and for better understanding of site specific ecohydrological relationships.

To improve the accuracy of the estimated evapotranspiration in the study area, more meteorological data like surface albedo, emissivity and solar net radiation should become available from a site specific meteorological station.

REFERENCES

[1] KUSTAS, W.P. AND NORMAN, J.M., 1996: Use of remote sensing for evapotranspiration monitoring over land surfaces. *Hydrological Sciences Journal, 41(4)*, pp. 495-516.

[2] BASTIAANSSEN, W.G.M., MENENTI, M., FEDDES, R.A. AND HOLTSLAG, A.A.M., 1998: A remote sensing surface energy balance algorithm for land (SEBAL) 1. Formulation. *J.Hydrol., 212-213*, pp. 198-212.

[3] BASTIAANSEN, W.G.M. AND ROOZEKRANS, H., 2003: Vlakdekkende actuele verdamping van Nederland operationeel beschikbaar. *Stromingen 9, no. 4*, pp. 5-19.

[4] HUYBRECHTS, W., BATELAAN, O., DE BECKER, P., JORIS, I. AND VAN ROSSUM, P., 2000: Ecohydrological research of wetland ecosystems in river valleys in Flanders (in Dutch), Final report VLINA project C96/03, Institute of Nature Conservation, Brussels, 281 pp + app.

[5] BATELAAN O., L.Q. HUNG, B. VERBEIREN AND F. DE SMEDT, 2004: Mapping of wetness gradients by hyperspectral sensing of phreatophytes. *Geophysical Research Abstracts, Vol. 6*, 06459.