Estimation of the areal evapotranspiration of the Ingói-berek in the Kis-Balaton wetland using Landsat-8 satellite images with two approaches

A kis-balatoni Ingói-berek területi evapotranszspirációjának becslése Landsat-8 műholdképek segítségével két megközelítéssel

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Abstract: When examining the water balance of lakes, the measurement and determination of evaporation and transpiration are the biggest problems. Evapotranspiration - as an output parameter of water balance- is very important in case of our largest lake, Lake Balaton and the associated Kis-Balaton Protection System. The evapotranspiration of the common reed (*Phragmites australis*) plays a decisive ecological role in the wildlife of the marshes. In case of Kis-Balaton, common reed is a significant factor due to the extent of its stands, which exceed 2,000 hectares. The latest solutions in evapotranspiration models are remote sensing models. We have tried to estimate the areal evapotranspiration with the red and near-infrared bands (NDVI, Normalized Difference Vegetation Index) of Landsat-8 satellite images using two different approaches: the use of FAO-56 potential evapotranspiration equation with local crop coefficients and the SEBAL model.

Keywords*: evapotranspiration; Landsat-8 satellite images; NDVI*

Összefoglalás: Állóvizeink vízháztartási mérlegének vizsgálata során a párolgás és párologtatás mérése, meghatározása jelenti az egyik legnagyobb problémát. Az evapotranszspiráció - mint a mérleg egyik legnagyobb kiadási paramétere - döntő fontosságú legnagyobb tavunk a Balaton és a hozzá tartozó Kis-Balaton Védelmi Rendszer működésében. A Kis-Balaton mocsarainak élővilágában meghatározó ökológiai szerepet betöltő közönséges nád (*Phragmites australis*) evapotranszspirációja jelentős tényező állományainak mérete miatt, mely a Kis-Balaton esetében 2000 hektárt meghaladó mértékű. Az evapotranszspirációs modellek legújabb megoldásait jelentik a távérzékeléses modellek. Landsat-8 műholdképek vörös és közeli infravörös spektrumaiból (NDVI) számítva végeztünk evapotranszspiráció becslést két módszer felhasználásával: helyben mért növénykonstansos megközelítést FAO-56 egyenlettel és a SEBAL modell futtatásával.

Kulcsszavak*: evaporanszsiráció, Landsat-8 műholdképek, NDVI*

1. Introduction

Many wetlands around the world are threatened by changes in water management, often with detrimental consequences for their ecosystems and the ecosystem services that are important to many people (Finlayson and D'Cruz, 2005).

The largest shallow freshwater lake in Europe is the Lake Balaton. Its natural filter, the Kis-Balaton wetland (KBW) is a crucial part of Lake Balaton's ecosystem, serving as a natural filter for the Zala River, which is the lake's primary water source (Hatvani et al., 2011). The site of this study, the Ingói-berek is a specific area within the Kis-Balaton wetland, and recent conservation efforts have focused on improving the habitat and preserving natural values in the Lake Balaton region.

Evapotranspiration (ET) is an important output component of the water balance. Accurate estimation of ET is crucial for optimal water resource management. The difficulties in calculating ET in wetlands can lead to inaccurate water balance estimations. Simple meteorological methods or off-site ET data are often used to estimate ET, but these approaches do not incorporate potentially important site-specific factors (Lott and Hunt, 2001).

Meteorological or climatological methods are based on-site point data, which cannot provide accurate approach of ET over large areas. Although the water balance method can estimate evapotranspiration at the watershed level, it works for a long time, usually one year, and cannot meet the requirements of short-term studies (Liu et al., 2006). Considering these problems, remote sensing methods are used to estimate actual ET (ETa), which provide pixel-scale ETa estimates for shorter periods over a large area. Most of these methods are based partly or fully on the energy balance principle, where net radiation is considered the main driver. The Surface Energy Balance ALgorithm (SEBAL) for land is a spatial ETa estimation method based on energy balance and satellite remote sensing techniques (Bastiaanssen et al., 1998).

The aim of this study was to detect the applicability of Landsat-8 satellite images in canopy cover detection (NDVI) as well as the use of SEBAL in ETa determination. The modelled ETa results were validated by locally measured estimations based on crop constants and use of FAO-56 equation.

2. Materials and Methods

An ETa study was carried out on the Ingói-berek, KBW at the end of August 2024. We chose the end of August as the sample day because the reed canopy had already reached its maximum size by this time. The area of Ingói-berek is about 440 ha, and one third of it is vegetation covered. The remaining part consists of fragmented reed and open water (Fig. 1).

The Landsat-8 L1 30 x 30 m resolution with less than 10% cloud cover images were downloaded from https://earthexplorer.usgs.gov on 28.08.2024.

Figure 1 *The NDVI of the Ingói-berek, Kis-Balaton wetland by Landsat-8*

We created a Normalized Differential Vegetation Index NDVI = (R-NIR)/(R+NIR) image from the red (R) and near-infrared (NIR) bands using the QGIS 3.28 (www.qgis.org) GIS software (Figure 1). We masked the 440-hectare Ingo area from the NDVI raster images. Then we classified the image by dividing the NDVI range into 3 equal parts. The upper interval: dense reed stand, the middle interval: transition between reed and water with submerged macrophyte, the lower interval: water with submerged macrophytes.

Calculation of ETa by locally measured data

The satellite images-based classification of the Ingói-berek was necessary due to the vegetation cover and the way of its ETa estimation by using crop coefficient and FAO-56 approach.

The daily reference evapotranspiration (ET_0) was calculated from the data of the Keszthely Agrometeorological Research Station (L: 46° 44’, W: 17° 14’ E: 124 m) using the FAO-56 formula (Allen et al., 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma\ \Delta(1 + 0.34\ u_2)} \qquad (1)$$

where Rn is the net surface radiation of the plant (MJ m^{-2} day^{-1}), G is the daily heat flux of the soil (MJ m^{-2} day^{-1}), T is the average daily temperature measured at a height of 2 m (°C), u2 is the wind speed measured at a height of 2 m (ms^{-1}), es is the saturation water vapor pressure (kPa), ea is the actual water vapor pressure (kPa), Δ is the slope of the water vapor pressure curve (kPa $°C^{-1}$), γ is the psychrometric constant (kPa $°C^{-1}$).

The actual evapotranspiration for the three classified areas was determined using the ETa plant constants for reed, submerged macrohytes and the transitional average of the two:

$$ET_a = K_c\ x\ ET_0 \qquad (2)$$

where Kc is the crop coefficient (Kc_reed: 1.23 (Anda, 2014), Kc_submerged_macrophytes: 1.04 (Anda,2016), Kc_average = transition: 1.14) and ET_0 is the daily reference evapotranspiration.

By multiplying the classified NDVI areas with the ETa we get the areal daily evapotranspiration for the Ingói-berek. We compared this value with the one calculated by SEBAL.

The SEBAL method

SEBAL calculates the total radiation and energy balance for each pixel. Evapotranspiration is derived from the instantaneous latent heat flux, λET (Wm^{-2}), and is calculated as the residual of the surface energy balance equation at the moment of satellite departure for each pixel:

$$R_n = G + H + \lambda ET \qquad (3)$$

where R_n is the net radiation in Wm^{-2},
G is the ground heat flux (Wm^{-2}),
H is the sensible heat flux (Wm^{-2}),
is the latent heat flux (Wm^{-2}), (λ is the latent
heat of evaporation, and ET is the evapotranspiration).

The net radiation (Rn) is calculated from the radiation balance of the earth's surface as follows:

$$R_n = (1 - \alpha)\ x\ R_s \downarrow + RL \downarrow - RL \uparrow - (1 - \varepsilon)\ x\ RL \downarrow \qquad (4)$$

where RS↓ is the incoming shortwave radiation (Wm^{-2}),
is the surface albedo (dimensionless),
RL↓ is the incoming longwave radiation (Wm^{-2}),
RL↑ is the outgoing longwave radiation (Wm^{-2}),
is the surface emissivity (dimensionless).

The ground heat flux (G) is estimated using the empirical relational function of Bastiaanssen (2000), using net radiance and some additional surface parameters such as albedo, surface temperature and normalized difference vegetation index (NDVI):

$$\frac{G}{R_n} = \frac{T_s}{\propto(0.0038\propto + 0.0074\propto^2)(1 - 0.98NDVI^4)} \qquad (5)$$

where Ts is the surface temperature in K.

The sensible heat flux (H) is a function of the temperature gradient, surface roughness and wind speed, and is therefore difficult to calculate due to the interaction of temperature gradient and surface roughness. The classical expression for sensible heat flux was given by Farah and Bastiaanssen (Farah and Bastiaanssen, 2001):

$$H = \rho\ x\ C_p\ x\ dT\ /\ r_{ah} \qquad (6)$$

Where H is the sensible heat flux,
the density of air (kg m^{-3}),
Cp is the specific heat of air (1.004 J/kg/K),
dT is the near-surface temperature difference in K,
and rah is the aerodynamic resistance to heat transport (m/s).

In the SEBAL model, a linear relationship is introduced between the surface temperature Ts and the calibrated dT based on the knowledge of two boundary conditions identified within the image, where the dT values can be calculated using the known H values at the two pixels.

$dT = aTs + b.$ (7)

To define the coefficients a and b, two pixels must be selected that represent extreme conditions of temperature and humidity, which are called hot and cold pixels. The cold pixel is a well-irrigated, fully covered cropland with a surface temperature (Ts) close to the air temperature (Ta). The hot pixel is a dry, bare agricultural area with a λET of 0. The two pixels connect the calculations of all other pixels between these two points. Starting from neutral stability assumptions, the sensible heat flux is iteratively estimated using the Monin-Obukhov atmospheric stability corrections.

Latent heat flux is the rate of latent heat loss at the surface due to evapotranspiration:

$$\lambda ET = R_n - G - H \qquad (8)$$

Evapotranspiration for the current time (mm/h):

$$ET_{inst} = 3600\ x\ \frac{\lambda ET}{\lambda} \qquad (9)$$

Where latent heat (J/K):

$$\lambda = 2.501 - (T_a - 273)\ x\ 0.002361 \qquad (10)$$

The reference ET ratio:

$$ETrF = ET_{inst}/ETr \qquad (11)$$

Where ETr is the reference ET for the given hour.
The daily ET is calculated from the daily reference ET:

$$ET_{24} = ETrF\ x\ ET_{r-24} \qquad (12)$$

Where the cumulative 24-hour ETr for the satellite leap day:

$$ET_{r-24} = \sum_h^{24} ET_{r-h} \qquad (13)$$

3. Results and Discussion

In the classified NDVI image of 28 August 2024, the three different areas are clearly distinguished in Figure 2: 61.5% reed, 28.2% transition between reed and water - submerged macrophytes, and 10.3% water - submerged macrophytes (Figure 2).

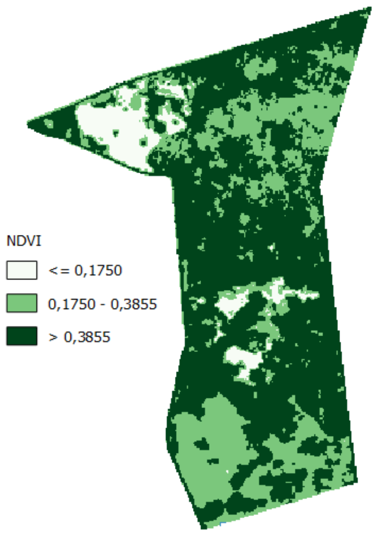
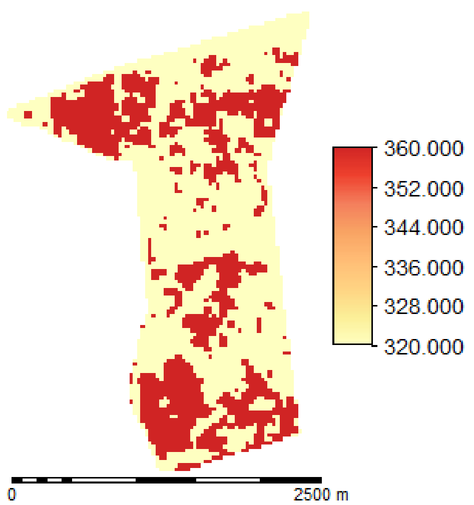
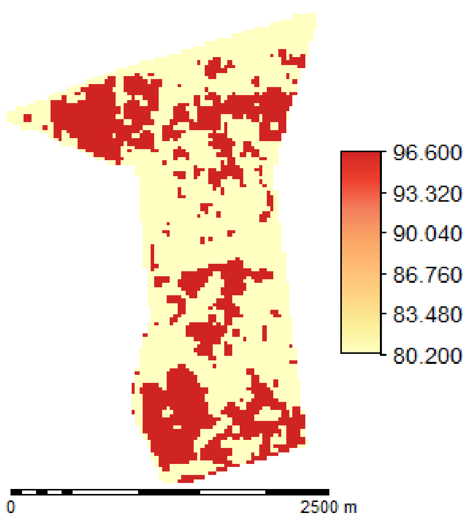


Figure 2 *The classified areas: white: water - submerged macrophytes, light green: transition, dark green: reed.*

We have summarized the energy balance components of the day (28.08.2024) calculated with SEBAL (Rn, G, H, λET) and the hourly and daily evapotranspiration calculated for the satellite time in Figure 3.

<table>
<tr><td>28.08.2024 Rn [W m^{-2}]</td><td>28.08.2024 G [W m^{-2}]</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>28.08.2024 H [W m^{-2}]</td><td>28.08.2024 λET [W m^{-2}]</td></tr>
</table>

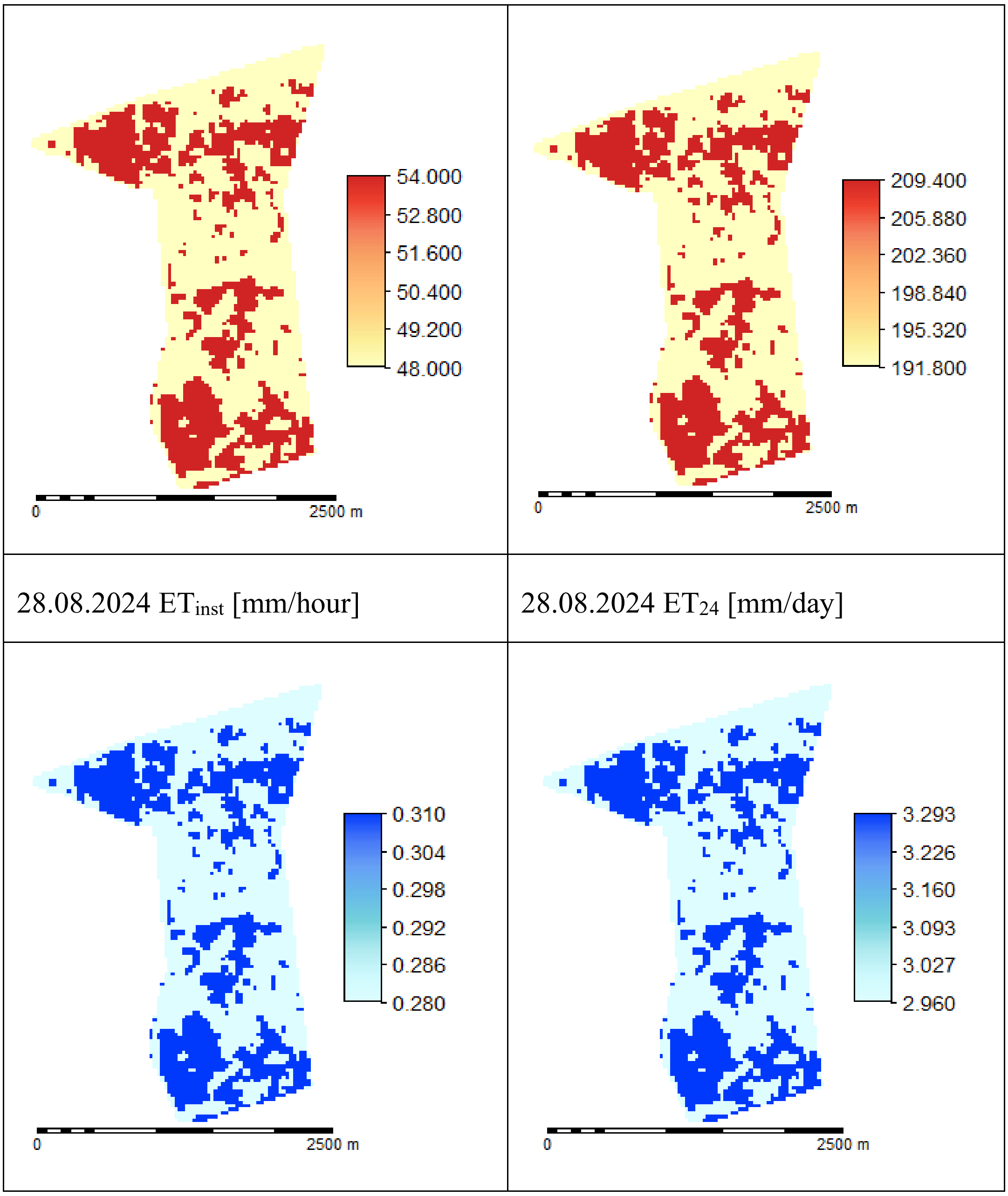


Figure 3 *SEBAL results for 28 August 2024 (Rn - net radiation, G - ground heat flux, H - sensible heat flux, λET - latent heat flux, ETins - ET for the current time, ET24 - 24-hour ET)*

The daily reference evapotranspiration calculated with the FAO-56 formula was 3.52 mm on the sample day of 28 August 2024. The comparison of the daily evapotranspiration calculated with the FAO-56 formula in Figures 4 and 5 clearly shows that SEBAL underestimates by 24%.

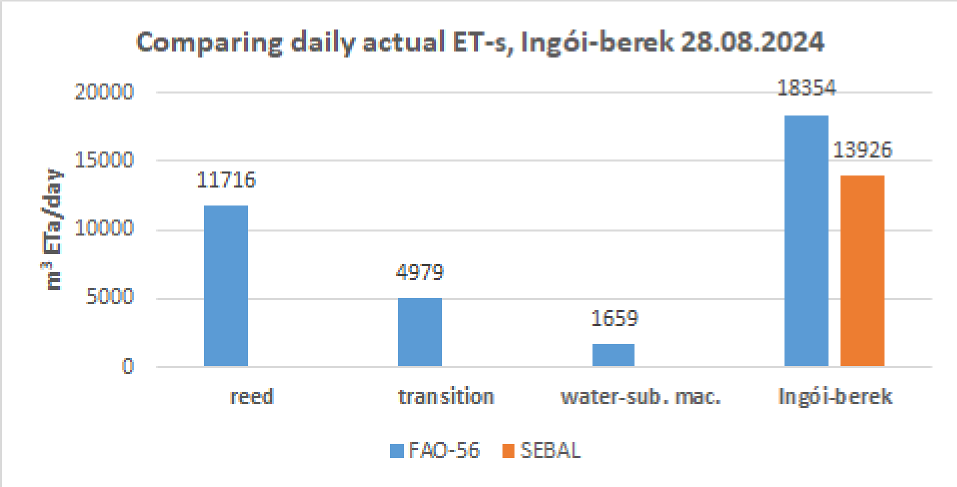


***Figure 4** Comparison of daily evapotranspiration in m³ for Ingói-berek 2024.08.28*

The daily evapotranspiration in m^3/day can be seen in Figure 4. For reed dominated area 11716 m^3/day, for the transitional area 4979 m^3/day and the water – submerged macrophytes area 1659 m^3/day were calculated. The actual evapotranspiration for whole area of Ingói-berek was 18354 m^3/day, which clearly exceeds the SEBAL-modelled value of 13926 m^3/day.

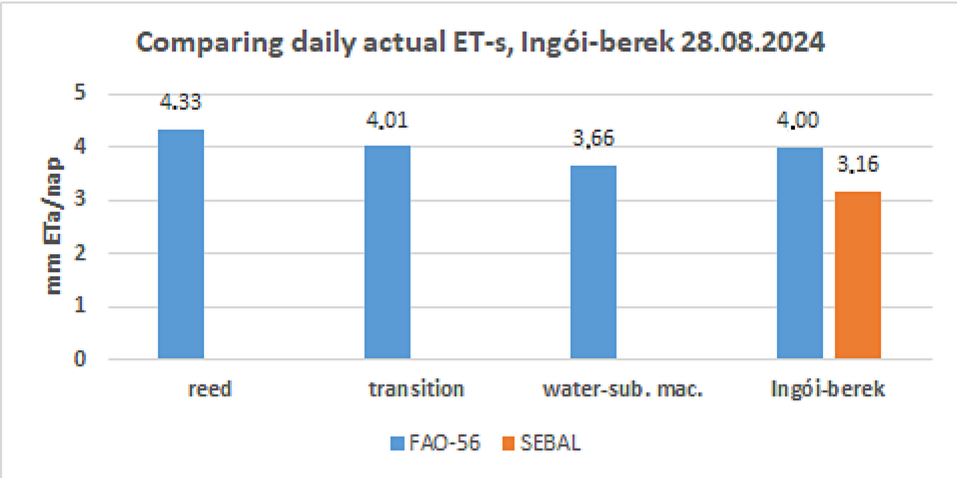


***Figure 5** Comparison of daily evapotranspiration in mm for Ingói-Berek 2024.08.28.*

The daily evapotranspiration in mm/day can be seen in Figure 5. For reed dominated area 4.33 mm/day, for the transitional area 4.01 mm/day and the water – submerged macrophytes area 3.66 mm/day were calculated. The actual evapotranspiration for whole area of Ingói-berek was 4.00 mm/day, which clearly exceeds the SEBAL-modelled value of 3.16 mm/day.

4. Conclusions

Calculating regional evaporation from freely available satellite remote sensing images is a complex but spectacular method. Satellite imagery has a distinct advantage when it comes to area coverage. Satellites can capture images of various areas, including remote and inaccessible regions. The Ingói-berek also provides a good example of estimating the coverage of hard-to-reach areas. The definition of evapotranspiration itself is quite problematic; each approach is subject to error, albeit to varying degrees. If we add to this the approximation error in the basic coverage data, the ET estimate as the largest output member in the water balance, deteriorates it further.

The modelling approach in ET estimation increasingly gaining ground in the literature. Based on local daily ETa calculation (crop coefficient), the difference between the daily modelled ETa amount 24%, which can be considered acceptable. In the future, satellite imagery will be indispensable for delineating hard-to-reach areas, which can be combined with the SEBAL model to estimate ETa, accurately. It can also be considered an advantage that satellite imagery presents a cost-effective solution compared to drones.

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