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Evapotranspiration estimation at the Kis-Balaton wetland

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Abstract— Evapotranspiration rate, ET_a and vegetation composition strongly influence the water budget of wetland impacting available water and water resource management. One of the goals of this study was to estimate the areal ET_a of the Kis-Balaton wetland, KBW (natural ecosystem) between 1997 and 2012. This time period was free of any human intervention. ET_a was accounted for different vegetation classes through the multiplication of the reference evapotranspiration, ET_0 by previously determined crop coefficients in each vegetation/open water classes. Besides common reed and cattail, five other groups were separated, including open water as an independent class. The evapotranspiration sums were strongly impacted by annual mean air temperature, T_a. One degree increment in annual average T_a will increase the yearly ET_a sums in about 100 mm. The yearly areal ET_a of KBW ranged from 737.08 mm to 896.63 mm with an average of 802.07 mm during the 16-year study.

1. Introduction

Crops, including wetlands, under the impact of solar radiation are influenced by such variables as temperature, water transport processes, crop growth, and production (*Burba et al.*, 1999). Partitioning of radiation and actual evapotranspiration, ET_a are strongly associated with the stage of vegetation.

Among others, *Abtew* and *Obeysekera* (1995) and *Allen et al.* (1998) discussed the methodology available for wetland's ET_a estimations. These wetland's areal ET_a approximations are similar to those of used in ET_a calculations of arable crops. Two options include direct measurements (lysimeter use, energy balance Bowen ratio, and/or eddy covariance techniques) and modeling approach.

The main limitations of direct measurements are the high cost of lysimeter maintenance and difficulties in their operation for other crops than wetlands (*Valiantzas*, 2006; *Zhou* and *Zhou*, 2009). This method also requires an expert laboratory (*Allen et al.*, 2011; *Wang* and *Dickinson*, 2012). In everyday practice, to get ET_a, crop coefficients, K_c are multiplied by reference evapotranspiration, ET_0. Limited generalizability of K_c exists from plant side, as types and distribution of crops differ greatly from place to place (*Drexler et al.*, 2004). Parallel with this assumption, different kinds of microclimatological models use a large number of hardly accessible inputs (meteorological and canopy surface data).

Anthropogenic interventions have modified the water level of Lake Balaton during the past two centuries. Two hundred years before, the establishment of the sluice of Sió canal and the extension of agricultural land declined the lake's water level drastically, causing serious water quality issues, mainly in the Keszthely-bay. To mitigate water quality deterioration, a new reconstruction project, the so-called Kis-Balaton Water Protection System (KBWS) was started at the end of the last century. Previously, severe cyanobacterial blooms deteriorated the water quality of the lake, that was published by *Tátrai et al.*, (2000). Two steps (I and II) were launched as the reconstruction of the Kis-Balaton wetland (KBW). The first step was completed in 1985, while an eutrophic pond (Hídvégi pond) was created by five-step flooding (*Korponai et al.*, 2010). The Hídvégi pond retained the nutrient loads causing overall improvement of the Balaton's water quality (*Hatvani et al.*, 2011). Phase II (Fenéki pond) operated the water level management of the wetland ecosystem synchronizing different habitats to avoid different conflicts. Reconstruction of KBWS was finished in 2016; an area is partly flooded, while other regions remained "untouched" habitats.

The geographical location of the study site, the Carpathian Basin which comprises Lake Balaton and the surrounding extended marshland, makes this region extremely vulnerable. Temperate zone formed in the basin has highly variable inter- and intra-annual precipitation and ET_a. This region is expected to have severe episodic droughts and floods, creating significant hydrologic lesions in response to human climate modification. In addition to weather variability, the on-site wetland ecosystems have little seasonal variability in green leaf area despite large seasonal variation in ET_a. A similar tendency was observed by *Garbulsky et al.* (2008) and *Anderson et al.* (2012) for Mediterranean wetlands. Due to these combined environmental specialties of temperate zone wetlands, attention was paid to improve the understanding of their ET_a peculiarities and their relevant controlling factors (weather variables and crop features). Wetlands differ in their energy regimes and exchange processes due to extent, fluctuating water levels, vegetation types, and geographical positions (*Kellner*, 2001). Therefore, on-site determined ET_a on daily timescale seems to be not appropriate to answer the many-sided questions relating to wetland's ET_a (*Admiral et al.*, 2006). One part of the study was dedicated to these local ET_a concerns on such a natural ecosystem as KBW. The reason for studying the selected period (1997–2012) was

the uninterrupted phase in the life of the KBW. There was no human intervention during this time; the ecosystem could be treated as a natural one. This phenomenon is not common in the history of KBW from the end of the 19th century.

2. Materials and methods

A 16-year-long areal evapotranspiration study was conducted at the KBW, and the Agrometeorological Research Station (ARS) of Keszthely (latitude: 46° 44′ N, longitude: 17° 14′ E, elevation: 124 m above sea level), Hungary. This meteorological station belongs to the observational network of the Hungarian Meteorological Service. A QLC-50 climate station (Vaisala, Helsinki, Finland) with a pyranometer (Kipp & Zonen Corp., Delft, the Netherlands) is operational at the ARS. Combined air temperature, T_a and humidity sensors are placed at a standard height of 2 m above the surface level. Signals from meteorological sensors are collected every 2 seconds, and 10-min averages are logged. Data of the station were used in both ecosystem parts, including soybean.

K_c of dominant macrophytes of KBW were measured previously (2005–2011) in the growing chambers of Thornthwaite-Mather type compensation evapotranspirometers with unlimited water supply. The surface area of growing chambers was 4 m², with a depth of 1 m. These containers were settled at the meteorological station located on the northern edge of the KBW. Daily water losses were expressed as a residual member of the water budget equation. Later on, based on these measured evapotranspirations, the K_c of different macrophytes was expressed. More details on this experiment were published in *Anda et al.* (2014). (The same instruments were used in the determination of soybean ET_a between 2017 and 2018; see also Section 2.1).

Wetland maps of the KBW were produced by the Central- and West-Transdanubian Water Directorate. To produce digital orthophotos, triangulation was used to get the absolute orientation elements of the aerial photographs. A high resolution digital elevation model (DEM) transformed the original images into orthogonally projected images (*Winkler*, 2004) with a final pixel size of 0.5 m. The long-term data were analyzed by a pixel-based approach in the Environment for Visualizing Images, ENVI version 4.7 software package (ITT, 2009). The used classification method was the maximum likelihood to get the main classes of the sample area (Fenéki pond). Training areas for the classification were selected from field observations. To draw the vegetation map, ArcMap version 9.3.1 software (ESRI User Manual 2009, CA, US) was applied. See more details in *Anda et al*. (2014).

The ET_a of Fenéki pond was estimated by multiplying the ET_o with the K_c of the related macrophyte class and by accounting the cover ratio of that class as follows:

$$ET_a = \frac{\sum_{i=1}^{6}(ET_0 K_{cai} A_i)}{\sum_{i=1}^{6} A_i} \quad , \tag{1}$$

where A is the area covered by the macrophyte and open water classes (1-6).

2.1. Statistics

The distribution of each ET_a series was checked by the Shapiro-Wilks test for normality. Square root transformation was performed to satisfy the assumption of normality. Long-term annual ET_a totals with a normal distribution (mm year^{-1}) were analyzed by a two-tailed t-test. All tests were carried out with SPSS Statistics version 17.0 software (IBM Corp., New York, USA).

3. Results and discussion

3.1. Composition of KBW

Based on the maps (ortophotograps) of the Hungarian Water Authority, the composition of the wetland was established between 1997 and 2012 (*Fig. 1*). Six classes were distinguished containing one open water and five macrophytes (*Crundell,* 1986) as follows:

Class 1. **Tall emergent macrophytes:** weed and two cattail species.
As there was no significant difference in ET_a (including C_k) between the reed and cattail, they were put together in the same category.

Class 2. **Leafy emergent macrophytes:** Three species of sedge included in the second class of macrophytes.

Class 3. **Woody shrub:** willow.

Class 4. **Grassland:** fescue, French ryegrass, foxtail.

Class 5. **Woody deciduous:** alder, cottonwood.

Class 6. **Open water:** incorporating seaweed.

The ratio and composition of the classes with their spatial ranges are presented in *Table 1*.

Due to the presence of seaweed in the water of Kis-Balaton, to derive the accurate evaporation, the Class A pan evaporation was modified, filling the pans with seaweed and littoral sediments (*Anda et al.*, 2018). About 15–20% increase in the "filled" pan evaporation was measured due to the above intervention.

The first two categories dominated the wetland canopy (40%+30%=70%). Outside of these two dominant classes, there was only one (Class 5), in which the cover ratio of a given class exceeded 10%. The cover percentage of all other groups fell well below 10%.

Table 1. Composition of KBW using vegetation and open water classes in the period of 1997–2012

| Classes	Type of habitat	Typical species (Latin names)	Common names	Cover		
				Mean %	Min %	Max %
Class 1	Tall emergent macrophytes	*Phragmites australis, Typha angustifolia, Typha latifolia*	reed cattail	40	39	42
Class 2	Leafy emergent macrophytes	*Carex acutiformis, Carexe lata, Carex riparia*	sedge	30	27	33
Class 3	Woody shrub	*Salix cinerea, Salix alba*	willow	5	4	6
Class 4	Grassland	*Festuca rupicola, Arrhenatherum elatior, Alopecurus pratensis*	fescue French ryegrass foxtail	8	6	9
Class 5	Woody deciduous	*Salix fragilis, Alnus glutinosa, Populus tremula*	willow alder cottonwood	11	10	11
Class 6	Open water (with submerged crops)	*Ceratophyllum demersum, Ceratophyllum submersum, Najas marina*	seaweed	6	6	7
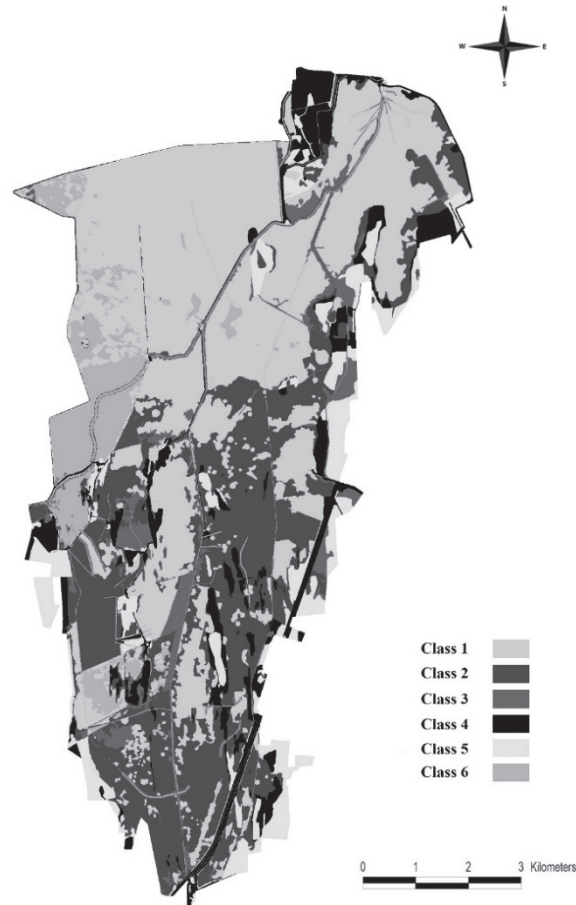
Fig. 1. Composition of macrophyte and open water classes in the KBW (*Anda et al.*, 2015). (class 1: tall emergent macrophytes; class 2: leafy emergent macrophytes; class 3: woody shrub; class 4: grassland; class 5: woody deciduous; class 6: open water ± seaweed)

3.2. ET_a of the wetland with T_a

On the basis of daily on-site measurements in evapotranspirometer/A pan and calculated ET_0 (*Allen et al.,* 1998), their ratios, the C_k/pan coefficients were derived for class 1, class 2, and class 4 from 2005 to 2011. In the remaining two vegetation classes (class 3, class 5) data of *Irmak et al.* (2013) were adopted. The actual ET_a equals to the multiplication of ET_0 by C_k. A detailed description of the process and C_k results were published in *Anda et al.* (2014).

Long-term daily mean ET_a of six wetland classes with different covers ranged from 2.87 (class 5) to 4.04 (class 1) mm day^{-1}, with the maximum of 4.45 mm day^{-1} (class 1) in 2012 and minimum of 2.62 mm day^{-1} (class 5) in 2005 (*Table 2*). The highest ET_a was always observed in reed canopy (class 1) and not in open water. Open water evaporation can also limited by the temperature profile over the water surface. When the water surface is colder than the surrounding air, and there is only weak wind, a cold cap can limit the evaporation processes, since in the cold

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air, the atmospheric humidity is higher. Although the derived l6-year daily mean ET_a of Fenéki pond (3.63 mm day^{-1}) was closer to the open water evaporation (3.66 mm day^{-1}) than that of the ET_a of classes with different crop covers. It is worth to remark that the cover of open water in KBW ranges between 6 and 7% only. The lowest daily mean ET_a was always observed in woody deciduous class, while the highest ones were in the two dominant macrophyte classes (class 1 and class 2). These two latter categories' results were comparable with that of 4.4 mm day^{-1} revealed by *Lenters et al.* (2011) for reed and cattail dominated wetland in Nebraska, USA, for almost the same environmental conditions as at the KBW. Similar daily mean ET_a results of 4.3 mm day^{-1} were obtained by *Irmak et al.* (2013) for a riparian plant community for Nebraska, for the same growing site as the previous citation of *Lenters et al.* (2011) mentions.

Table 2. Daily mean evapotranspiration (mm/day) of six the wetland classes with different covers and areal evapotranspiration of the whole Fenéki pond between 1997 and 2012

Year	Class 1	Class 2	Class 3	Class 4	Class 1	Class 6	Fenéki pond
			[mm day^{-1}]				
1997	3.87	3.36	3.04	3.13	2.77	3.53	3.47
1998	3.76	3.25	2.97	3.05	2.68	3.42	3.38
1999	3.81	3.29	2.99	3.07	2.71	3.45	3.41
2000	4.36	3.77	3.42	3.53	3.09	3.96	3.92
2001	4.10	3.52	3.19	3.30	2.86	3.70	3.66
2002	4.22	3.61	3.24	3.37	2.98	3.77	3.77
2003	4.32	3.73	3.40	3.49	3.09	3.92	3.89
2004	3.75	3.27	3.01	3.06	2.69	3.44	3.39
2005	3.71	3.20	2.88	2.99	2.62	3.35	3.33
2006	3.83	3.29	2.98	3.07	2.71	3.44	3.43
2007	4.24	3.64	3.30	3.41	2.97	3.81	3.80
2008	4.05	3.51	3.19	3.28	2.88	3.68	3.65
2009	4.07	3.53	3.24	3.31	2.91	3.72	3.68
2010	3.75	3.21	2.92	3.01	2.64	3.36	3.36
2011	4.36	3.80	3.46	3.55	3.13	4.00	3.94
2012	4.45	3.86	3.54	3.61	3.20	4.05	4.02
Mean	**4.04**	**3.49**	**3.17**	**3.27**	**2.87**	**3.66**	**3.63**

During the observation period, the 16-year annual ET_a totals of different classes ranged from 745.98 (class 5) to 974.81 mm (class 1) with a weighted average of 896.63 mm for the Fenéki-pond. The most important statistical characteristics are presented in *Fig. 2*. According to the daily mean ET_a results of vegetation and open water classes, the highest yearly ET_a sums were observed in reed (cattail) followed by the open water, which result was very close to spatial ET_a sum of the whole Fenéki pond. In case of Fenéki-pond, the annual weighted mean ET_a of warm years increased with 11.45% ($p<0.001$) in comparison to cool year's ET_a water losses, suggesting that almost 100 mm difference in wetland's ET_a was manifested in favor of warm periods.

On the basis of the 16-year study, the largest water consumer in the Kis-Balaton was the reed and cattail (class 1), occupying almost half of the wetland area (*Fig. 3*). The second in line is the sedge (class 2), contributing at about a third of the total water use. Annual mean water losses *(ET_a* or evaporation) of all the other vegetation/open water classes contributed less than 10%.
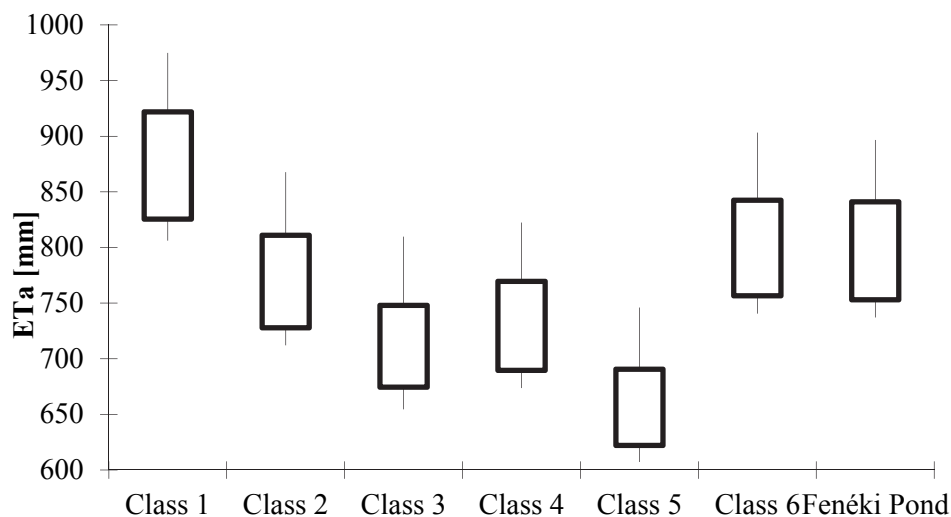
Fig. 2. Box-plot for the annual evapotranspiration totals, ET_a in different vegetation and open water classes between 1997 and 2012. The bottom and top of the boxes represent the 25th and 75th percentiles. The vertical lines that end in horizontal strokes above and below each box are from the upper and lower hinges to the upper and lower adjacent values.
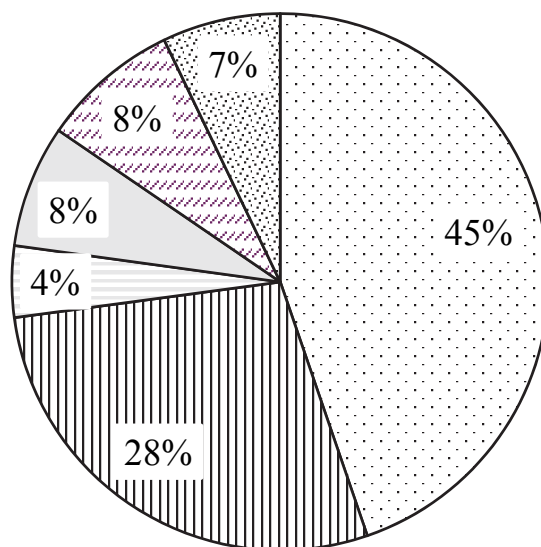
Fig. 3. Contribution of different vegetation/open water classes to the evapotranspiration of the Fenéki pond.

Yearly mean T_a of KBW was 10.8 °C between 1997 and 2012. The 1971 to 2000 climate norm of 10.3 °C was half-degree lower than that of the annual mean T_a during the investigation period. Out of sixteen years studied, seven cool (T_a<10.8 °C: 1997, 1998, 1999, 2004, 2005, 2005, 2010) and nine warm years (T_a>10.8 °C: 2000, 2001, 2002, 2003, 2007, 2008, 2009, 2011, 2012) were distinguished, which might be decisive for the wetland's ET_a. The difference in annual average T_a between cool (10.1 °C) and warm years (11.3 °C) equalled to 1.2 °C (p<0.001). It is worth to notice that all warm years were registered after 2000.

To evaluate the potential impact of annual mean T_a versus ET_a total, linear regression was fitted (*Fig. 4*). Based on the slope, 1 °C increment in annual T_a significantly increased the ET_a totals by 61.7 mm, with a relatively low RMSE of 23.9 mm/year. The scatter in the data was higher at cooler years.
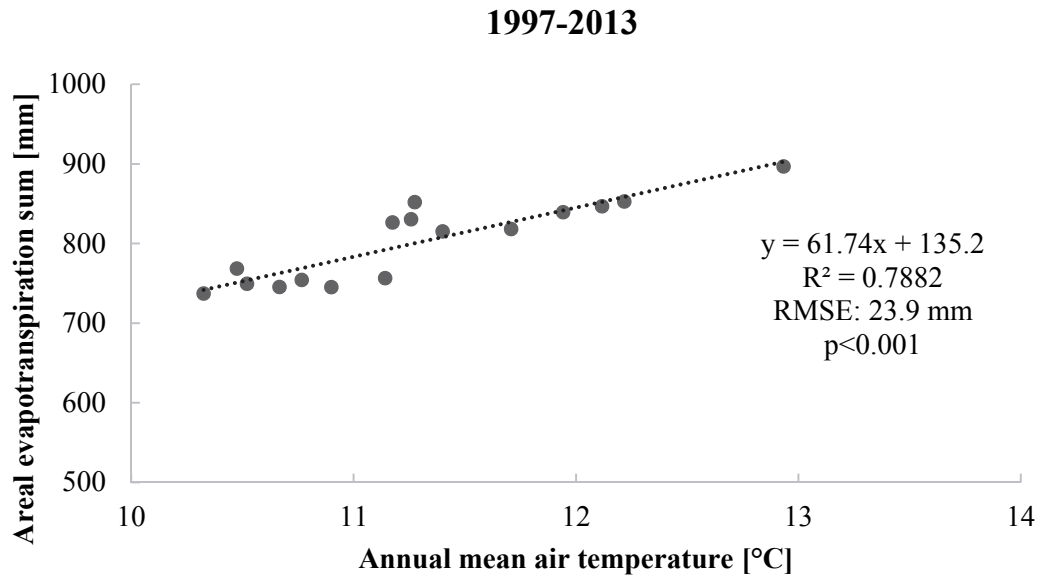
1997-2013

$y = 61.74x + 135.2$
$R^2 = 0.7882$
RMSE: 23.9 mm
$p < 0.001$

Fig. 4. Regression between annual mean air temperatures vs areal evapotranspiration totals at the KBW between 1997 and 2012.

4. Conclusions

In the KBW, the climatic norm (1971–2000) of annual precipitation sum is 634.2 mm with the wettest and driest monthly precipitation sums of 78.5 mm in July and 31.1 mm in January, respectively. Comparison between long-term annual ET_a sums and climate norm of precipitation confirmed only 70.7% of the ET_a entering by precipitation at the KBW. Other inputs are also needed to balance the water budget of the wetland. The governing terms of a wetland water balance are the ET_a and the precipitation (*Soja et al.,* 2013), making the system vulnerable to the negative impacts of the climatic change through variable rainfall events. Monitoring these governor factors would help for water authorities to mitigate issues related to the water level of KBW and Lake Balaton that are embedding on the system due to upcoming climate change.

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