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Actual and reference evapotranspiration for a natural, temperate zone fen wetland – Upper Biebrza case study

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Abstract: Evapotranspiration is the key and predominant component of the water balance in wetlands. Direct evapotranspiration measurements are challenging in wetlands due to their remoteness and high surface water level. This article describes the actual (*ETa* and reference evapotranspiration (ET_0) from a cultivated wet meadow located in the Biebrza National Park – the largest national park in north-east Poland, Central Europe. The data were sourced from a micrometeorological station equipped with an eddy covariance system to measure heat and vapour fluxes and such meteorological elements as radiation balance components, air temperature and humidity. The values of directly measured *ETa* were presented daily in the context of available energy and ET_0. Daily sums of *ETa* ranged from below 0.2 mm in winter to 6.5 mm in summer. The share of daily sums of *ETa* in the ET_0 usually ranged from 50 to 60%, with extreme values from 10 to 170%.

Aside from giving more insight into Biebrza wetlands' functioning, the actual data produced in this study may be used instead of indirect methods, which were used the most in modelling wetlands areas.

Keywords: actual evapotranspiration, Biebrza, eddy covariance method, reference evapotranspiration, wetlands

INTRODUCTION

Wetlands are exceptionally complex and relevant for life on Earth ecosystems, being a specific reservoir of water and biodiversity, and play a significant role in climate change prevention and mitigation as a chain in water, energy and carbon cycles.

Although wetlands still cover a global area of 1.2 billion ha, they are declining fast, with 35% losses of natural wetlands since 1970 (Gardner and Finlayson, 2018). Despite increasing awareness of their importance and threats, wetlands deterioration is still a fact, confirmed by the latest report of Ramsar Convention 2021 (Dudley (ed.), 2021). The quality of remaining wetlands is also suffering due to drainage, pollution, invasive species, unsustainable use, disrupted flow regimes and climate change. Despite this high pressure, Poland may still boast of the largest natural wetland complex in Western and Central Europe – the Biebrza Wetlands. Due to its unique characteristics, the Biebrza wetlands are considered a reference site for similar wetlands research (Wassen *et al.*, 2006).

Water is one of the most important factors determining the status of wetland ecosystems in the Biebrza River valley. Protecting wetland habitats depends on maintaining high surface and groundwater levels, which is necessary to provide adequate moisture levels in wetland soils and prevent them from drying out and degrading (Kardel *et al.*, 2009). For this reason, many studies have studied the water balance, water resources modelling and water management in the Biebrza River valley. Actual evapotranspiration (*ETa*), in turn, is the key and predominant component of the water balance in wetlands (Přibáň and Ondok, 1985; Wessel and Rouse, 1994; Drexler *et al*., 2004) and is considered to be the most challenging component of the balance to determine. It can be assessed indirectly by observing differences in the water-table level (Carlson Mazur, Wiley and Wilcox, 2014) or by using the Bowen ratio (Abtew and Obeysekera, 1995; Kleniewska *et al*., 2015). Alternatively, it can be measured directly using lysimeters (Abtew and Obeysekera, 1995) and the eddy covariance method (Kowalska *et al*., 2013; Siedlecki *et al*., 2016a, Siedlecki *et al*., 2016b). Since measurement of evapotranspiration is challenging (Drexler *et al*., 2004; Abtew and Melesse, 2012; Stan *et al*., 2016), especially in impenetrable terrain such as wetlands due to the high surface water levels and variable plant cover. For this reason, studies based on direct measurements are not common, and in hydrological practice, *ETa* is often assessed using reference evapotranspiration (ET_0) calculated by Penman-Monteith.

So far, the *ETa* for the Biebrza River valley was determined mainly indirectly using the Thornthwaite method based on potential evapotranspiration (*ETp*), calculated using the French-modified Penman method (Poretta-Brandyk *et al*., 2011), through observation of changes in the groundwater table in connection with the Penman-Monteith method (Grygoruk *et al*., 2014), and using the heat balance and the Bowen ratio method (Kleniewska *et al*., 2015). The exceptions are research carried out with the eddy covariance method at the single micrometeorological station in the Middle Basin by Fortuniak and Siedlecki (Fortuniak *et al*., 2013, Siedlecki *et al*., 2016a, Siedlecki *et al*., 2016b). Yet, until now, the direct *ETa* measurements were not reported for any other location at the Biebrza River valley.

It is worth emphasising as the Biebrza River valley is longitudinally zoned into three different sub-regions: upper, middle and lower Basins representing different hydrogeological, hydrographic and geomorphological conditions. Individual parts determine the type of hydrological supply, and thus also the nature and specificity of the habitat conditions and the occurrence of the so-called bi-directional ecological zoning of the Biebrza valley (Oświt, 1968). These conditions can also determine the amount of evapotranspiration, but their effect has not been investigated yet.

This research aims to present results of direct measurements *ETa* in the difficult terrain conditions of a typical cultivated wet meadow located in the Upper Biebrza River basin and to trace and describe their dynamics. Presented *ETa* values may be used instead of indirect methods for hydrological modelling to improve their accuracy. The research was focused not only on a quantitative description of the physical processes of evapotranspiration in Biebrza wetlands but also contributed to the discussion on spatial variability of the evapotranspiration and their reasons along the Biebrza River valley and wetland areas at all.

The results of direct evapotranspiration measurements will finally contribute to database building on this area and similar wetlands. It is necessary to protect them effectively as it strongly influences water balance and water-dependent habitats.

In this study, we present the results of 2.5 years eddy covariance measurements of *ETa* at the temperate zone fen wetland. We discuss directly measured *ETa* in the context of available energy and ET_0 on a daily scale.

STUDY MATERIALS AND METHODS

STUDY MATERIALS

The study area is located in the Biebrza National Park (Pol. Biebrzański Park Narodowy – BPN) the largest national park in Poland, also listed as a Ramsar and Natura 2000 site. The BPN is situated along the densely meandering Biebrza River, and it is the country's largest complex of fen wetlands. The Biebrza River valley boasts a unique mosaic and zonal arrangement of wetland habitats, accommodating endangered plant and animal species.

One of the main sources of the water supply of Biebrza's wetland ecosystems is springtime river flooding (Keiser *et al*., 2014), which develops mainly due to melting snow cover (Berezowski, Chormański and Batelaan, 2015; Berezowski *et al*., 2019). At the moraine-valley frontier, groundwater is an essential part of the water supply (Anibas *et al*., 2012). The diversity of water sources contributes to maintaining a zonal arrangement of wetland habitats (Wassen *et al*., 2006), whose composition is further diversified by locally discontinued agricultural cultivation (Opdekamp *et al*., 2012). This transverse vegetation zoning is the most characteristic and clear in the Lower Biebrza.

The upper course of the Biebrza River valley is mainly peat that covers an area exceeding 14,000 ha with a depth 3–6 m. At the same time, the middle and lower sub-regions are mainly peat-silt and alluvial sections. There are no floods in the peat zone except in areas very close to the river. Mainly groundwater, slope and seepage waters are active here. In the western part of the Upper Biebrza valley, sedge communities are present only in areas of immersive zone located along the river. In turn, moss habitats dominate in areas located slightly higher fed by groundwater. The areas of the eastern part are almost entirely covered by various types of sedge-moss communities (Dembek, Oświt and Rycharski, 2005).

The high value of the Biebrza River valley vegetation is that rare plant communities of peatlands stretch here over many kilometres, many of which are listed in Annex I of the Habitat Directive (Council Directive, 1992).

The study site (micrometeorological station hereafter called Zosia station) was located in Rogożynek village, in the Upper Biebrza Basin, which is 34 km long and 6–7 km wide (Fig. 1). There are typical soligenious fens, i.e. with relatively little restriction of water outflow but kept wet by the constancy of water supply, mostly groundwater discharging into the fen (Wassen *et al*., 2006). The irregularly appearing floods are restricted to a narrow belt of 10–20 m along the river.

The climate of the Biebrza River valley is temperate transitional, with evident continental influences. Depending on the observation period, the climatological annual mean air temperature for Suwałki (the nearest meteorological station) is from 6.9 to 7.2°C, and the annual sum of precipitation is around 600 mm (Tab. 1). The basin features a mixture of various climate conditions where different types of soil and vegetation exist, leading to local and micro-scale climate variations. This diversity is mainly found in temperature and humidity conditions in the warm part of the year (Kossowska-Cezak, 1984).

The data from the micrometeorological station Zosia (53°42' N, 23°24' E) were used in this study. The station was situated in a homogenous, extensively used wet meadow (not fertilised,

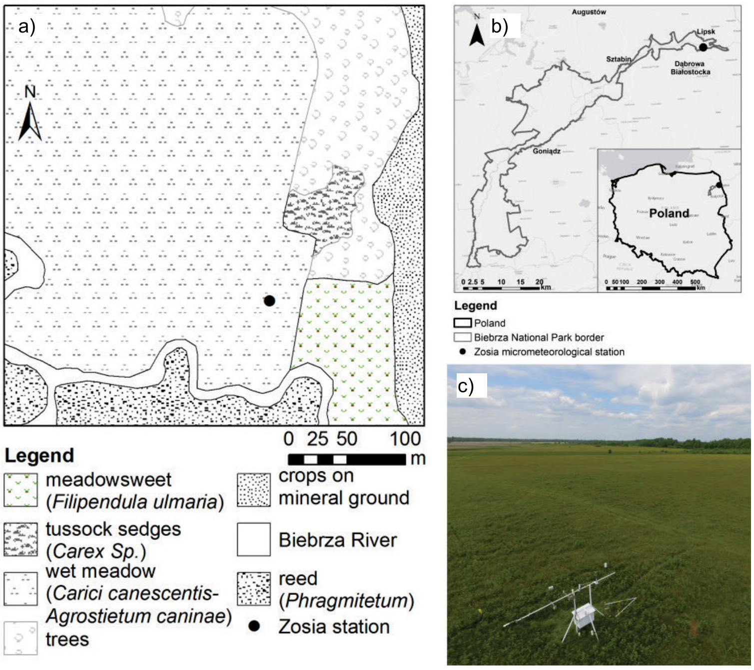

Fig. 1. Location of the micrometeorological station Zosia: a) surroundings of the station, b) map of the Upper Basin, c) view of the station; source: own elaboration

Table 1. Meteorological elements for Suwałki and Zosia stations

Station	Period	*T* (°C)	*P* (mm)	*f* (%)	*v* ($m \cdot s^{-1}$)
Suwałki	1981–2015[1)]	6.9	606.1	82.4	3.6
	1991–2020[2)]	7.2	607.1	–	–
	2015[2)]	8.3	593.3	77.8	3.5
	2016[2)]	7.7	665.8	80.7	3.3
Rogożynek (Zosia station)	2015[3)]	8.3	362.9	77.4	2.3
	2016[3)]	7.8	502.5	81.7	2.2

Explanations: *T* = air temperature, *P* = precipitation, *f* = relative humidity, *v* = wind speed.
Source: [1)] Fortuniak and Pawlak (2016), [2)] data of Institute of Meteorology and Water Management, National Research Institute, IMGW-PIB, [3)] own study.

mowed once a year). The wet meadow in the station's location, covered with *Carici canescentis-Agrostietum caninae* is also present in the north-west and west sections of the research area (Fig. 1). Fifty meters south of the station, the Biebrza River meanders, with reeds growing behind it, are present. Thirty meters east, there are tussocks of sedge, with meadowsweet (*Filipendula ulmaria*) and shrubs which are cut off when they grow above the average height of the prevailing plants. Fifty meters north-east and north from the station, a group of alder trees and willow shrubs exist.

At the Zosia station, basic meteorological measurements were collected, and for latent (*LE*) heat flux eddy covariance method was used. Continuous measurements recorded at the station include:

a) fluctuations of the movement of the air in three directions (u, v, w in $m \cdot s^{-1}$) using an ultrasonic anemometer, WindMaster Pro (Gill Inc., GB), located 3.5 m above ground;
b) fluctuations of the water vapour concentration (q ($mmol \cdot m^{-3}$), for *LE*), using a fast closed-path gas analyser, Licor 7200 (Li-COR, USA), located 3.5 m above ground;
c) temperature (T, °C) and relative humidity of the air (rH, %) at four levels (50, 100, 200, 350 cm), using HP 155 thermohygrometers (Vaisala, FIN);
d) net radiation (R_n) using a CNR4 radiometer (Kipp&Zonen, NL), installed at the height of 3 m;
e) precipitation, using a SEBA rain gauge, measured as 0.1 mm pulses.

Fluctuations of air movement and water vapour concentration were measured at 10 Hz frequency, and the rest of the elements were logged every 15 s. Finally, 30-minute mean values of meteorological elements were determined. The measurement period was from June 2014 to December 2016, excluding malfunction time of the station: 26–31 October 2014, 17 July 2015, 2–15 August 2015, 29 November 2015 and 1 September 2016.

Our station's air temperature and precipitation were compared with the data obtained from the meteorological station in Suwałki (Tab. 1) provided by the Institute of Meteorology and Water Management, National Research Institute (Pol. Instytut Meteorologii i Gospodarki Wodnej – Państwowy Instytut Badawczy – IMGW-PIB).

STUDY METHODS

The eddy covariance method was utilised to measure turbulent latent flux (*LE*). The principles of the method, its advantages, drawbacks and possibilities, as well as different ways of data processing, were described in details by Aubinet, Vesala and Papale (2012).

Based on the measured fluctuations in air mass movement and water vapour concentration, 30-minute values of *LE* were calculated in EddyPro software (ver. 5.2.1, LI-COR Inc., USA).

Simultaneously with calculating heat and water vapour fluxes to assess the quality of the raw time series, statistical tests recommended by Vickers and Marth (1997) were carried out: amplitude resolution, dropouts, absolute limits, skewness and kurtosis. Spike count/removal was conducted following the recommendation of Mauder *et al.* (2013). The data were also subject to the following procedures: compensation for the fluctuation of air density (Burba *et al.*, 2012), correction for spectral losses (Moncrieff *et al.*, 1997), flagging according to the Carbo Europe standard (Mauder and Foken, 2004) and footprint calculations (Kljun *et al.*, 2004). For more detailed footprint analysis, the procedure and the online application proposed by Kljun *et al.* (2015) was applied. The so-called climatological footprint indicated that in each month, on average, 70% of the signal reaches the sensor from the meadow area around the station where a sedge community prevails. In the warm half of the year, the 80% isoline closes the area, which includes the stretch of the Biebrza River meandering south of the station and a small portion of the reeds.

The 30-minute values of *LE* was characterised by the following 30-minute quality figures: (i) best quality data: 38%, (ii) data which can be considered for an annual balance: 32%, (iii) the worst quality data which should be removed from the set: 19%, (iiii) missing data: 11%. Moreover, values whose friction velocity (u^*) was lower than 0.1 m·s^{-1} were removed from the dataset along with the worst quality data subset producing in a total of 45% for *LE* of missing data. Gaps in the time series of *LE* was filled (for periods with available basic meteorological data) using the procedure proposed by Reichstein *et al.* (2005) and the R software (R Core Team, 2022) with the REddyProc package (Reichstein *et al.*, 2016). *LE* was non-adjusted for energy balance closure.

In order to determine daily values of ET_0, the standardised reference evapotranspiration equation for tall crops was used (Allen *et al.* (eds.), 2005):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{C_n}{T+273}\right)u_2(e_s - e_a)}{\Delta + \gamma(1 + C_d \cdot u_2)} \tag{1}$$

where: R_n – G = available energy (MJ·m^{-2}) obtained as diurnal sums from 30-minute values measured at the Zosia station; R_n = net radiation (MJ·m^{-2}) was measured at Zosia station; G = soil heat flux density was calculated as $0.1R_n$; γ = psychrometric constant (0.065 kPa·°C^{-1}); C_n = constant for tall crops (equal 1600 for daily time step); C_d = constant for tall crops (equal 0.34 for daily step); T = mean daily air temperature (°C) calculated as a mean value of maximum and minimum daily temperature from Zosia station; e_a = the actual vapour pressure (kPa) calculated from 30-min values of relative humidity and air temperature from Zosia station; daily means were calculated based on the obtained 30-min values; e_s = saturation vapour pressure (kPa) determined using equation:

$$e_s = 0.6108 \exp\left(\frac{17.27T_{30}}{T_{30} + 237.3}\right) \tag{2}$$

where: T_{30} = 30-min of air temperature from Zosia station;
u_2 = wind speed at 2 m above ground surface (m·s^{-1}) calculated as:

$$u_2 = u_z\left(\frac{4.87}{\ln(67.8z_w - 5.42)}\right) \tag{3}$$

where: z_w = height of wind speed measurements above ground surface (m); u_z = wind speed at z_w at above ground surface (m·s^{-1}); Δ = the slope of the saturation vapour pressure-temperature curve calculated as:

$$\Delta = \frac{2503 \cdot \exp\left(\frac{17.27}{T+237.3}\right)}{(T + 237.3)^2} \tag{4}$$

The equation (1) is recommended for the growing season; therefore, calculations were carried out using data collected from April to September.

RESULTS AND DISCUSSION

THE WEATHER DURING THE TIME OF OBSERVATION

In the analysed period (July 2014–December 2016), the mean annual air temperature (T) at Zosia station was 8.3°C in 2015 and 7.8°C in 2016. The temperature at the nearest meteorological station Suwałki was very close and equal to 8.3°C in 2015 and 7.7°C in 2016. The study period at Zosia station turned out to be warmer (2016) and exceptionally warmer (2015) than the climatological mean of 6.9°C (Tab. 1). Years 2014 and 2015 had a record warm July (20.1°C) and August (18.6°C), respectively. The coldest month in the research area was January 2016, with temperature of −5.3°C (1.7°C lower than the climatological average for this month (Fortuniak and Pawlak, 2016)).

The mean T in the analysed period ranged from −17.0 to 25.7°C (Fig. 2). In winter, the temperature was usually between −5.0 and 5.0°C, but there were a few days with daily temperature below −10.0°C. Negative values of T also occurred in the spring months (March–May); however, peak values of that season reached 22.0°C. The values of T, which were most often recorded in spring, ranged from 5.0 to 15.0°C, and in summer, from 15.0 to 20.0°C (with the highest T of that season reaching 26.0°C). In autumn, T was the most variable, ranging from −10.0 to more than 20.0°C.

The meteorological element that considerably affects the actual evapotranspiration (*ETa*) rate is the water vapour pressure deficit (*VPD*). The annual mean values of *VPD* in 2015 and 2016 were quite comparable: 3.1 and 3.7 hPa, respectively (Fig. 3).

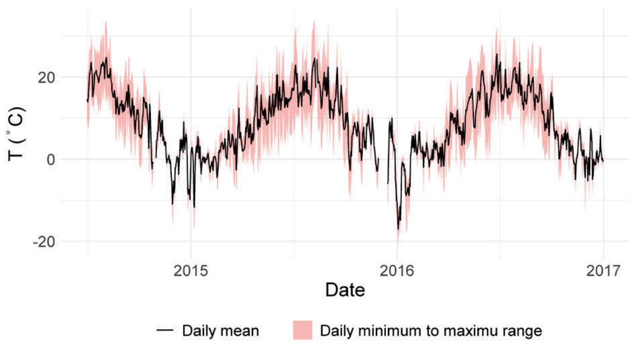

Fig. 2. Daily mean, maximum and minimum air temperature (T_d) at the Zosia station from July 2014 to December 2016; source: own study

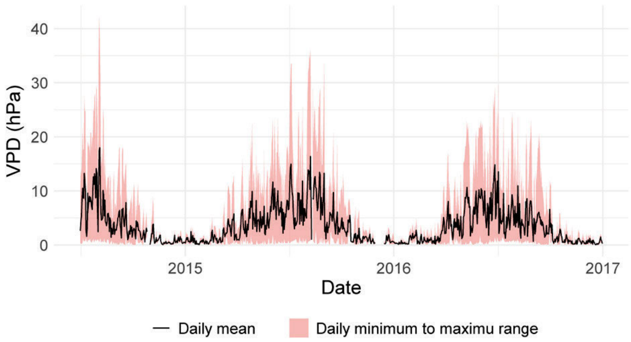

Fig. 3. Daily mean, maximum and minimum vapour pressure deficit (*VPD*) at Zosia station from July 2014 to December 2016; source: own study

Daily values of *VPD* ranged from about 3.0 hPa in winter to about 10.0 hPa in autumn and 18.0 hPa in summer. The maximum daily *VPD* exceeded 40.0 hPa and was observed in August 2014.

Another meteorological element significantly affecting *ETa* is wind speed (*v*). The mean wind speed in the analysed period was 2.2 $m \cdot s^{-1}$, with the lowest daily values recorded in summer (1.8 $m \cdot s^{-1}$) and the highest – in winter (2.8 $m \cdot s^{-1}$). Except in winter, *v* did not exceed 5 $m \cdot s^{-1}$ (Fig. 4).

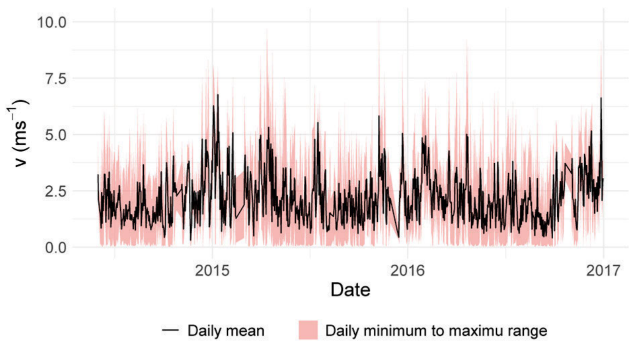

Fig. 4. Daily mean, maximum and minimum wind speed (*v*) at the Zosia station from July 2014 to December 2016; source: own study

The annual sums of precipitation for 2014 and 2016 were lower than the climatological mean of 608 mm (Tab. 1), and they were largely influenced by the summer rainfalls: almost 47 and 44% of the annual sum, respectively, occurred between June and August. An exceptional daily sum of precipitation reached 59.4 mm and was observed in July 2014.

A dry 2015 was observed (60% of the climatological mean) with a very dry summer and the lowest monthly sum of precipitation (4.7 mm in August).

The statistical analysis proved strong correlation between *ETa* and *VPD* and incoming solar radiation, with the correlation coefficient of 0.91 and 0.90 for *VPD* and for solar radiation, respectively.

ACTUAL EVAPOTRANSPIRATION (*ETa*) IN THE CONTEXT OF AVAILABLE ENERGY

From January, latent (*LE*) heat flux increased as more and more energy became available, and in April, it reached 47 $W \cdot m^{-2}$, which accounted for 24% of net radiation (R_n) (Tab. 2). The increase in solar radiation and higher air temperature led to the development of turbulent latent and sensible heat fluxes, and the LE/R_n between March and April increased only slightly: from 0.24 to 0.29. The LE/R_n ratio is raised rapidly and reached 0.43 between April and May (Tab. 2). It was due to intensive – vegetation development at the beginning of the growing season. Generally, in the north-eastern part of Poland, the growing season starts late; in the multiannual period (1971–2015), it began in the middle of April (Ciężkowski *et al.*, 2018). Therefore, the results show that transpiration has a major share in the water vapour flux within the analysed area.

Table 2. Average daytime (30-min values from 10 a.m. to 2 p.m. UTC+1) latent heat flux (*LE*) and net radiation (R_n) and LE/R_n ratio from 7 July 2014 to 31 December 2016 at Zosia station

Month	R_n	*LE*	LE/R_n
	$W \cdot m^{-2}$		
Jan	37.7	4.2	0.11
Feb	94.9	11.2	0.12
Mar	193.3	47.0	0.24
Apr	279.2	81.3	0.29
May	383.1	166.2	0.43
Jun	437.0	228.4	0.52
Jul	388.0	182.7	0.47
Aug	342.9	176.3	0.51
Sep	278.6	136.3	0.49
Oct	155.3	46.2	0.30
Nov	53.6	13.1	0.24
Dec	38.0	5.2	0.14

Source: own study.

Similar changes in the increase of the LE/R_n ratio in the warm part of the year were observed in Kopytkowo, located in the middle basin of the Biebrza River (Siedlecki *et al.*, 2016b). From February to April, a slight increase in LE/R_n was observed (successively by 0.28, 0.30 and 0.35) and a notable increase to 0.48 in May. There is also an interesting feature of the LE/R_n ratio in Kopytkowo. The contribution of *LE* in the net radiation was about 0.10–0.12 higher than at Zosia station (upper basin) in the warm half of the year, and the differences are even more evident in winter.

In a daily course, the highest 30-minute mean values of *LE* were recorded in June (228 $W \cdot m^{-2}$, Tab. 2), which was the month when as much as 52% of the available energy was used in evaporation. In the lower part of the Biebrza valley, Kleniewska *et al.* (2015) detected throughout the entire 4-week data series (July–August) the mean 30-min latent heat flux of 194 $W \cdot m^{-2}$ as the highest values in the outgoing portion of the heat balance. It is due to the typical course of green biomass in the sedge community with the pick observed in August (Chojnicki *et al.*, 2012).

The dominance of *LE* in the heat balance was observed in a boreal peatland fen (61°56'N, 50°13'E) of north-western Russia, where during the unfrozen months, LE/R_n was >60% (Runkle *et al.*, 2014). More energy for evapotranspiration was detected for clear days in the Trebon Basin (48°49'–49°20'N; 14°39'–15°00'E) near the Czech–Austrian border (Huryna, Brom and Pokorny, 2014). On a wet meadow dominated by high sedges (*Carex acuta*, *Carex vesicaria*, *Calamagrostis canescens*, *Phalaris arundinacea*, *Urtica dioica*), LE/R_n ratio reached 0.90.

At Zosia station, about 50% of R_n used for *LE* is observed to September. From September to the end of the year, the *LE* decreased, and the characteristic daily course of *LE* was maintained in October, but the maximum 30-minute values did not exceed 50 W·m^{-2} (Tab. 2). In November and December, similarly to the beginning of the year, no clear daily pattern of *LE* was observed, and the flux values reached just 13 W·m^{-2}.

DAILY VALUES OF ACTUAL EVAPOTRANSPIRATION (*ETa*)

One very dry (with annual precipitation of 362.9 mm) and one normal (with annual precipitation of 502.5 mm) year were observed in 2015 and 2016, respectively. The annual sum of *ETa* in dry 2015 was 526 mm, while in 2016, it was 427 mm. The difference results from changeable meteorological conditions observed in May, July and August. For example, in August 2015, there was noticeably less precipitation, and air temperature and the water vapour deficit were higher than in August 2016, which led to a difference of 73 mm in monthly *ETa* (134 mm in 2015 and 61 mm in 2016). Similar findings for the whole year showed investigations conducted in Salmisuo (62°46'N, 30°58'E), located in North Karelia, eastern Finland (Wu *et al*., 2010). In this near-pristine boreal mire complex, the latent heat fluxes in the dry year 2006 had a higher cumulative *ETa* than in the wet year 2007.

The mean daily *ETa* during the growing season (April–September) at the Zosia site was 2.1 mm in 2016 and 2.6 mm in 2015, with the maximum daily rate of *ETa*, which equals 4.7 mm in 2016 and 6.5 in 2015. Our results are in line with the mean daily *ETa* for the wetlands constituting the boreal peatland fen of north-western Russia (Runkle *et al*., 2014). This site had *ETa* averaging 2.5 mm·day^{-1}, with a maximum daily rate of 5.6 mm·day^{-1} during the growing season.

Daily *ETa* in winter (Fig. 5) usually remained below 0.2 mm (in more than 90% of the cases). Occasional high values (0.7 mm) observed in that season were related to a considerable increase in air temperature, water vapour pressure deficit and wind speed.

In spring (Fig. 5), when more energy reached the ground and vegetation developed, daily *ETa* sums grew from 0.2 mm in March to more than 3 mm in May 2015 (4 mm in May 2016).

When plants were fully grown in summer (Fig. 5), the variability of daily *ETa* was mainly due to changeable weather conditions. The summer (June–August) course of *ETa* did not reveal any regularity, and daily sums ranged from 0.3 to 5 mm (mean 2.8 mm). Our results for a seasonal (April–September) mean daily *ETa* rate (2.2 mm) agreed well with the results of Sun and Song (2008) in China (47°N) for a sedge-dominated marsh (2.3 mm·day^{-1}). A higher seasonal daily *ETa* average of 3.2 mm·day^{-1} has been reported for a sedge-grass swamp in former Czechoslovakia (Přibáň and Ondok,1985) and 3.7 ±0.23 mm·day^{-1} for a sedge community (*Carex acutiformis*, *Carex elata*, *Carex riparia*) at Kis-Balaton wetland (46°39'N; 17°12'E), in Hungary (Anda *et al*., 2015).

In autumn, daily *ETa* decreased more or less regularly (Fig. 5). At the beginning of September, sums of about 2.5 mm were observed, whereas, at the end of November, they did not exceed 0.1 mm. An exceptionally high sum of 3.6 mm was observed on September 1, 2015 due to the presence of hot tropical air masses in Poland.

ACTUAL EVAPOTRANSPIRATION (*ETa*) IN THE CONTEXT OF REFERENCE EVAPOTRANSPIRATION (ET_0)

The daily values of reference evapotranspiration (ET_0) in the analysed months (from April to September) ranged from 0.4 to 7.3 mm. The distribution of ET_0 was similar year to year, with a maximum in June; however, the diversity of its values between the years 2014–2016 results from changes in meteorological conditions. Fermor *et al.* (2001) detected similar ET_0 ranging from 0.2 to 6.3 mm in their study of natural reed wetlands at Himley, England (52°31'N).

The ratio of ETa/ET_0 (known as a crop coefficient, *kc*) was from 0.10 to 1.7 (Fig. 6), with a mean seasonal (IV–IX) value of

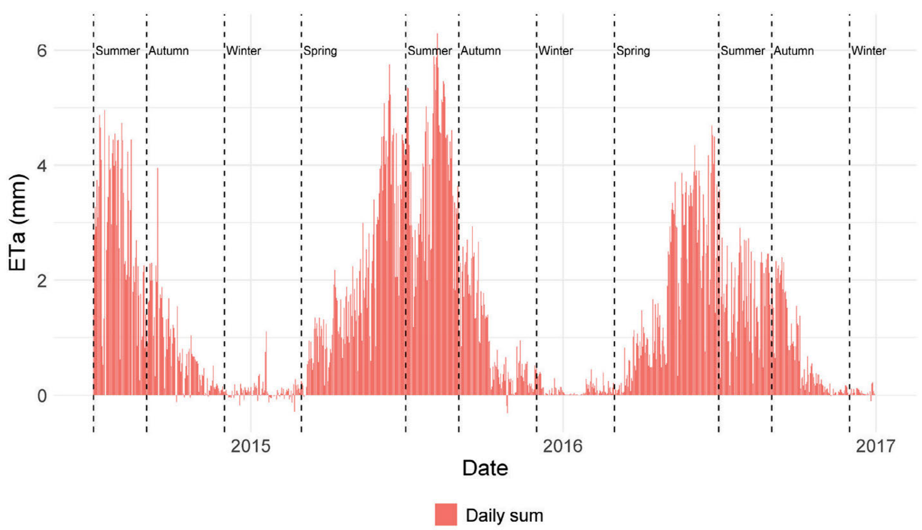

Fig. 5. The daily sum of *ETa* in four seasons of the year at Zosia station from July 01, 2014 to December 31, 2016; source: own study

Fig. 6. The daily crop coefficient ($kc = ETa/ET_0$) at Zosia station, DoY = day of the year; source: own study

0.66. A wide range of daily ETa/ET_0 ratios from 0.5 to 3.15 was noted for the aforementioned wetland (Fermor *et al.*, 2001).

At the Zosia site, we registered 17 days on which *ETa* exceeded ET_0. Almost 55% of daily ETa/ET_0 ratio cases were in the range of 0.5 to 0.8, with the maximum frequency in the range of 0.6 to 0.7 (23% of cases). In general, decrease in daily *kc* values during the rainy periods was observed. The area around the station is occasionally flooded after heavy rains. Such situation took place during the measuring period in July 2014. During that time, daily *kc* increased from 0.43 (rainy period) to 0.91 (flood event).

July and exceeded this value in August. On the other hand, in the wet July of 2016, the ETa/ET_0 reached only 0.6.

Tabulation of *kc* values for meadows and pastures indicates on their high, site/ecosystem dependent diversification (Pereira *et al.*, 2023). For Poland, *kc* values range from 0.45 (Kasperska-Wołowicz and Łabędzki, 2006) to 0.96 (Szejba, 2011) at the beginning of vegetation period for one-cut meadow. Szajda and Guz (1983), in turn, reported *kc* values from 0.25 to 0.83 for the same phase of vegetation in pasture. The range of values obtained in this study (Tab. 3) for the beginning of vegetation period is similar to the results cited above, in subsequent vegetation phases,

Table 3. Decadal ETa/ET_0 ratio in the period 2014–2016 at Zosia station

Year	Month																	
	Apr			May			Jun			Jul			Aug			Sep		
	decade																	
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
2014	–	–	–	–	–	–	–	–	–	0.7	0.6	0.7	0.7	0.7	0.6	0.6	0.6	0.6
2015	0.5	0.4	0.4	0.4	0.5	0.7	0.7	0.6	0.8	0.7	0.9	0.9	–	–	0.8	0.9	0.8	0.8
2016	0.4	0.5	0.4	0.6	0.7	0.7	0.8	0.7	0.8	0.5	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.7

Source: own study.

From April to mid-May, the mean ETa/ET_0 ratio was 0.4–0.5 in a 10-day period, increasing from early May and reaching almost 0.8 in June (Tab. 3). The ETa/ET_0 courses were similar in 2015 and 2016 from the beginning of the growing season until the time the vegetation was fully grown. The only haying activities on the analysed wet meadow took place in the first ten days of July (as a rule). From July to the end of September, substantial variability in ETa/ET_0 is observed between individual years. In the hot and dry year of 2015, 10-day ETa/ET_0 reached almost 0.9 in

it is, however, significantly lower than reported by other authors and equals from 1.10 to 1.30.

CONCLUSIONS

This study reports 2.5 years of *ETa* and ET_0 in different meteorological conditions at the temperate zone fen wetland. A dry and exceptionally warmer 2015 was observed with a very dry and record warm August, while 2016 turned out to be warmer than the climatological mean with normal annual precipitation. The annual sum of *ETa* in 2015 was 526 mm (with 134 mm in warm and dry August); in 2016, it was 427 mm.

The mean daily *ETa* in the growing season was 2.1 mm in 2016 and 2.6 mm in 2015. Depending on plant activity and the weather conditions, the daily *ETa* account for 10 to 170% of ET_0. The ETa/ET_0 ratio was the lowest in early spring (equal to 0.4 for 10-day) and doubled by the middle of summer. In the hot and dry months of 2015, 10-day ETa/ET_0 reached almost 0.9 in July and exceeded this value in August, while in the wet July of 2016, the ETa/ET_0 reached only 0.6.

Results of this study showed a substantial difference in evapotranspiration under different meteorological conditions in individual years.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

DATA AVAILABILITY

The data from Zosia station used in this paper can be shared upon request.

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