Analecta Technica Szegedinensia

Vol. 14, No. 2 ISSN 2064-7964 2020

ESTIMATED SEASONAL DAILY EVAPOTRANSPIRATION RATES FOR A HORIZONTAL SUBSURFACE FLOW CONSTRUCTED WETLAND

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Received: August 13, 2020 • Accepted: November 16, 2020

ABSTRACT

We measured the daily evapotranspiration on a horizontal sub-surface flow constructed wetland in Hódmezővásárhely, Hungary. The main focus of our research was the seasonality of evapotranspiration in this CW. We measured the water balance of the CW and searched days when no precipitation, no inlet or outlet impacted on the water balance of the constructed wetland, only the evapotranspiration. had impact on the water balance. The results show that in spring the evapotranspiration rates were between 18-42,6 mm/day, in summer 12,3-42,3 mm/ day and in autumn the values were 13,6-22,7 mm/day. The highest hourly evapotranspiration was 16,3% of the daily evapotranspiration. This value was 415 % of the average, hourly hydraulic load that can significantly affects on the effluent concentration. The results also show the morning and evening condensation which has two main effects. On the other hand, the water balance of the CW is increased, which results the decrease of the concentration of wastewater.

Keyword: horizontal subsurface flow constructed wetlands, evapotranspiration, tufted sedge, condensation, water balance

1. INTRODUCTION

Constructed wetlands (CWs), also known as treatment wetlands, are sustainable and efficient solutions used around the world to treat wastewater. There are two main types of constructed wetlands, free-surface flow systems (FSF-CW), and sub-surface flow systems (SSF-CW). SSF-CWs can be constructed with the wastewater flowing either horizontally (HSSF-CWs) or vertically (VSSF-CW) through the substrate that supports the growth of plants.

The two components of evapotranspiration that can negatively affect the water balance of constructed wetlands by causing loss of water are the transpiration of plants and the evaporation from the water surface and soil [1], [2]. Under warm and windy environmental conditions, evapotranspiration can be high [3], [4], [5].

The rate of evapotranspiration mostly depends on climatic factors, such as precipitation, temperature and wind [6], as well as the growth [7] and height of the plants in the system and the density of the leaves [8] [9]. Plants also play a key role in determining water loss in a CW [10].

Pedescoll *et al.* [11] showed that the evapotranspiration in subsurface flow constructed wetlands was 20–22 mm/day, the water loss via evapotranspiration was around 44% of the hydraulic load, but there were days when it reached 100%. Freedman *et al.* [12] measured similar values of 20 mm/day but observed 40 mm/day in certain times of the day. In another study, values of evapotranspiration in HSSF-CWs fluctuated between 19.5 and 40 mm/day [13].

Tuttolomondo *et al.* [14] measured evapotranspiration in a constructed wetland in Italy and observed that on some summer days evapotranspiration reached 25–35 mm/day; this value was 20–30% of the hydraulic load. Tanner [15] studied a evapotranspiration rates of a constructed wetland during a hot (30-33 °C) summer in New Zealand, the values measured were around 7.1–11.7 mm/day meaning that transpiration accounted for 20% of the daily hydraulic load.

DOI: https://doi.org/10.14232/analecta.2020.2.1-12

Milani *et al*. [16] investigated evapotranspiration rates in twelve pilot-scale horizontal subsurface flow constructed wetlands in eastern Sicily in which they had five different species. The results showed that the evapotranspiration rates varied between 7,35 to 17,31 mm/ day.
Queluz *et al.* [17] had similar values in pilot-scale HSSF-CWs, their results were 4,9 to 20 mm/day, nevertheless, they obtained very high results at around 46 mm/day. They did not find the exact reason for this extreme value.
Yano *et al.* [18] studied the influence of the plant growth on the evapotranspiration. The results showed that the evapotranspiration increased the growth of the plants, and that there were weeks when the water loss via evapotranspiration increased up to 80 % of the inflow rate. Hamouri *et al.* [19] measured the water loss via evapotranspiration in HSSF-CWs in Marocco. They concluded that the water loss amounted to 11-17 % of the inflow rate.
Chazarenc *et al.* [20] estimated evapotranspiration using a 1 m^2 pilot-scale constructed wetland planted with Common reed (*Phragmites australis*). The evapotranspiration water loss accounted for 13–40% of the hydraulic load. The results showed that in constructed wetlands evapotranspiration increased hydraulic retention time and decreased dispersion [20].
As a result of evapotranspiration, concentration of solutes increases in constructed wetlands [21]. The highest evapotranspiration rates in a HSSF-CW were found to occur at midday, at around 12:00 to 13:00 [22], [23].
Bialowiec *et al.* [9] measured the pollutant removal efficiency of constructed wetlands under different evapotranspiration rates and concluded that higher evapotranspiration caused higher effluent concentrations. In another study of the relationship between evapotranspiration and removal efficiency, the results showed that increased rate of evapotranspiration positively affected outflow Biochemical Oxygen Demand (BOD_5) and Chemical Oxygen Demand (COD) concentrations [24].
The above findings show that evapotranspiration indirectly affects effluent water quality, thus it is imperative to obtain in-depth knowledge about evapotranspiration in subsurface flow constructed wetlands. Among the many studies on water management processes of surface flow constructed wetlands [25] [26] [27], only a few contain detailed water balance analysis of subsurface flow constructed wetlands [20].
These studies are not enough detailed about these viewpoints:

- Don't show any information about morning and evening condensation processes.
- Don't show enough detailed analysis of separation between daytime and night time periods.
- Don't show enough detailed analysis of changing the hourly evaporation rates.

These detailed information are very important because the effluent concentration of wastewater can be changed dynamically in a day by the highly changing evaporation rates, and condensation processes.
In this study, our aims are to estimate the answers to these interesting scientific viewpoints. Otherwise, we don't know so detailed analysis of CW's evaporation processes from the Middle-European region.

2. MATERIALS AND METHODS

2.1. Study site

Our study site was a subsurface flow constructed wetland treatment plant near Hódmezővásárhely (Hungary). This constructed wetland treats 1-1.5 m^3 of wastewater per day from a dairy farm. The technology consists of a septic tank, a pump system, VSSF-CW planted with common reed (*Pragmites Australis*), HSSF-CW planted with Tufted sedge (*Carex elata* All.), a polishing pond and a trickling system planted with poplar trees (*Populus* spp). This study focuses exclusively on HSSF-CW.

2.2. Species description

Tufted sedge is a widespread species found all over Europe, except for the Mediterranean. This species is native to Hungary and is generally abundant throughout much of its Central European range

DOI: https://doi.org/10.14232/analecta.2020.2.1-12

(http://www.iucnredlist.org). It can be found in shallow water, preferring oligotrophic to eutrophic and often calcareous freshwater habitats, and in seasonally flooded areas. The primary life form of the species is perennial and aquatic. Tufted sedge grows as a tussock-forming graminoid, often forming extensive stands. Being a Eurasian temperate flora element, it presents broad ecological tolerance to light as well as the moisture, nitrogen and salt content of the soil. It can be up to 40-120 cm tall, has a triangular shape and is very rough at the top (https://www.brc.ac.uk/plantatlas). The cross section of the leaf is M-shaped, the blade is 2-5 mm wide, greyish-green, and the underside of the leaf is dull. Tufted sedge is a hypostomatic plant, which means that the stomatal openings for gas exchange are on the underside of the leaf [28]. Stomatal openings are also generally found on the leafy floral shoots (personal observation). Mostly in summer, drained soil conditions can strongly decrease the stomatal conductance-induced transpiration rate [29].

2.3. Measurement method

For investigation of the daily fluctuation, we were looking for days characterized by:

- No inflow and outflow
- No precipitation
- Significant decrease in daily water levels

Apparently, the change in water level on these days depends only on the extent of evapotranspiration. A significant amount of daily water level change was needed to eliminate measurement inaccuracies in the water pressure transmitters. Water level observations were recorded at 10-s intervals on the test days to an accuracy of 0.1 mm (± measurement error). We found 16 days to test. Three water level pressure transmitters were installed in the object under investigation. Perforated pipes were placed vertically in the CW. The level transmitters were placed in these pipes, and all three series of data were used and the values measured were averaged by the 3 pressure transmitters so that we could eliminate measurement errors and thus accurately track hourly changes.

3. RESULTS AND DISCUSSION

The measurement data values provided by pressure transmitters and the average values generated from them, and figure 1. below, shows data for day 2012-05-24.

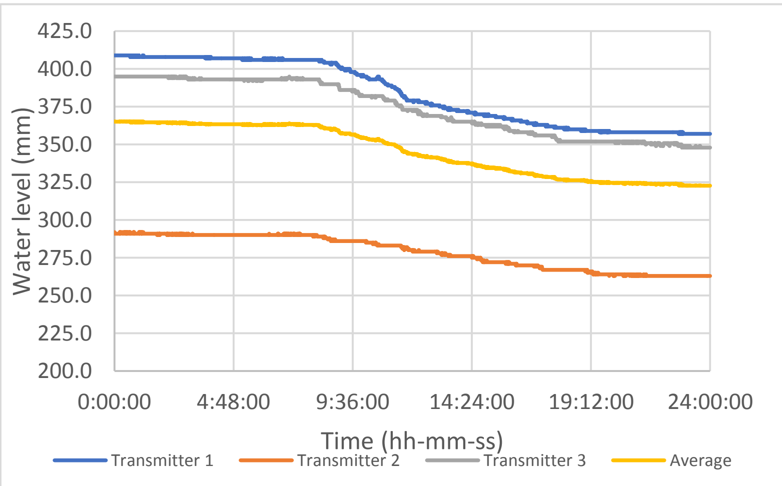

Figure 1.: Registered water levels

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The significant difference between the water level values is due to the different depths of the transmitters. For the purposes of this study, the position of the transmitters is not relevant. From our viewpoint, only the degree of water level change is important. It can be clearly seen from all 4 functions shown that during the night period the water level change is lower than during the day. This can be explained by increased evapotranspiration during the day.

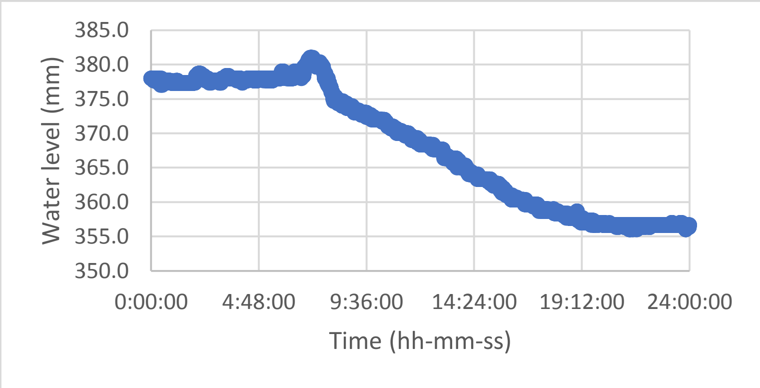

Figure 2: Evolution of average water level on the date of 2011-08-29.

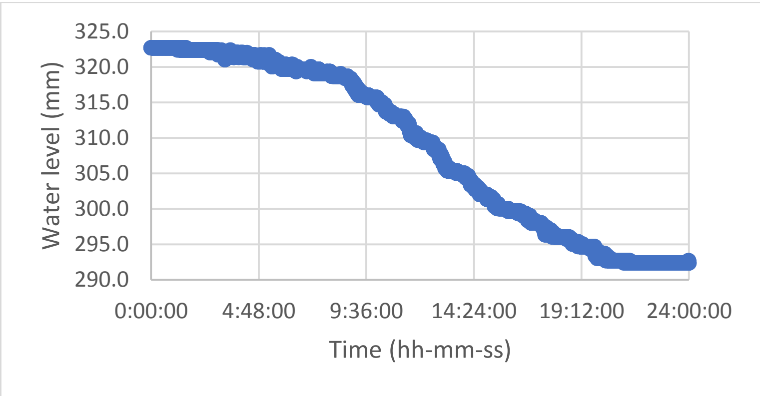

Figure 3: Evolution of average water level on the date of 2012-05-25

We have produced values of water level change as illustrated by the following figures. The two figures (Figure 2. and 3.) are noteworthy as the second figure shows a gradual decrease in water level during the day, while the first figure demonstrates an increase in the water level due to condensation after sunrise and sunset.

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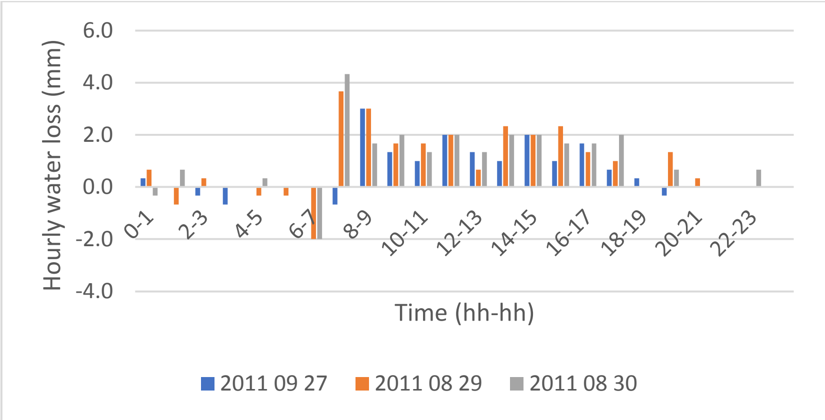

Figure 4.: Hourly changes in water level during the day

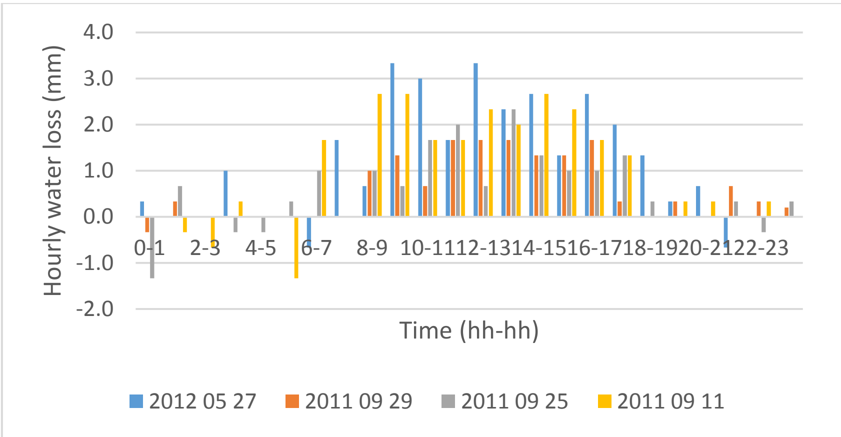

Figure 5.:Hourly changes in water level during the day

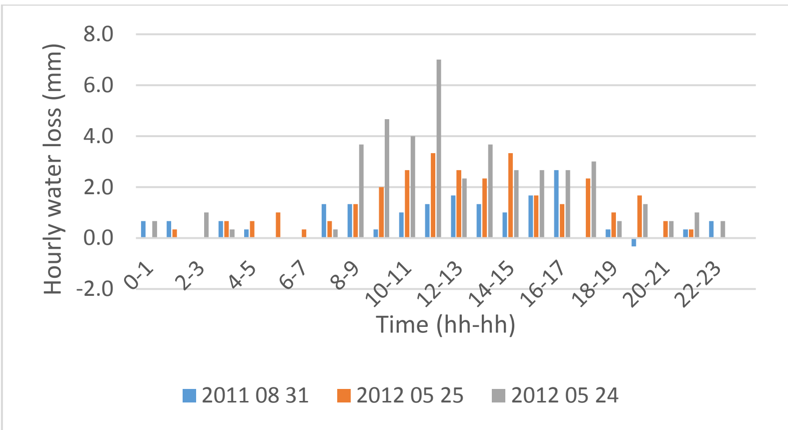

Figure 6.:Hourly changes in water level during the day

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Analecta Technica Szegedinensia
Vol. 14, No. 2 ISSN 2064-7964 2020

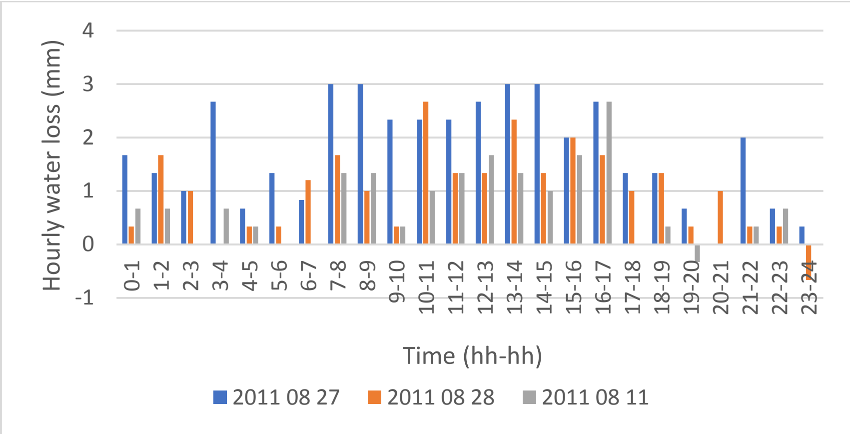

Figure 7.:Hourly changes in water level during the day

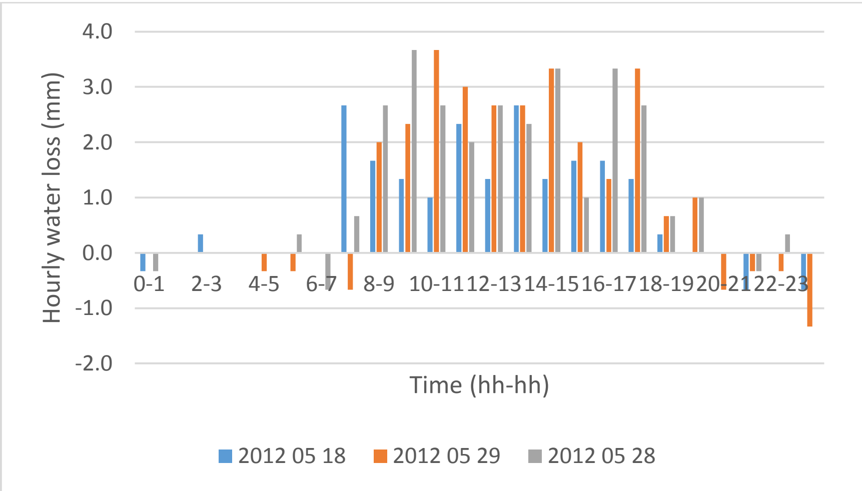

Figure 8: Hourly changes in water level during the day

Figure 4-8. show the hourly calculated water loss values. The measured days were divided into 3 groups. Values found in the first group are shown on figures 4 and 5. Here, due to the effect of morning condensation, negative values appear after sunrise. The highest hourly water change values were recorded by the transmitters One hour after sunrise. Further research is needed to explore the underlying cause.
In the second group, as shown on Figure 8, we didn't calculate negative values at morning but also at night (neither in the morning nor during the night did we calculate negative values). The values show that on 2012-05-29, this effect lasted several hours. The highest water loss values were between 10 am. and 14 pm.
In the third group, shown on Figures 6 and 7, there was no morning or evening condensation and the water loss gradually increased to its maximum at around 12 -13 pm. and then gradually decreased. On 2012-05-24, the maximum hourly water loss reached 7 mm/hour. The highest daytime water loss and the highest nighttime water loss were also recorded on this day.

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Table 1: The data for measured days

	Sunrise	Sunset	Daily hour (hh:mm)	Nightly hour (hh:mm)	Average daily temperature (C°)	Water level changes at day (mm)	Water level changes at night (mm)	Daily water level changes (mm)
2011.08.11	5:27	20:00	14:33	9:27	17	9,0	3,3	12,3
2011.08.27	5:49	19:31	13:42	10:18	26	30,3	12,0	42,3
2011.08.28	5:50	19:30	13:40	10:20	22	20,0	4,3	24,3
2011 08 29	5:53	19:26	13:29	10:31	22	22	-0,3	21,7
2011 08 30	5:54	19:24	13:30	10:30	23	19,7	2	21,7
2011 08 31	5:55	19:22	13:27	10:33	21	14	3,7	17,7
2011 09 11	6:09	19:01	12:52	11:08	24	23,7	-1	22,7
2011 09 25	6:27	18:33	12:05	11:55	16	14,4	-0,8	13,6
2011 09 27	6:29	18:29	12:00	12:00	18	14,4	-0,7	13,7
2011 09 29	6:32	18:25	11:53	12:07	17	12,7	1	13,7
2012 05 18	5:02	20:08	15:07	8:53	14	19,7	-1,7	18
2012 05 24	4:56	20:15	15:19	8:41	20	38,6	4	42,6
2012 05 25	4:55	20:16	15:21	8:39	20	28,3	2,1	30,4
2012 05 27	4:54	20:17	15:23	8:37	17	25	2	27
2012 05 28	4:53	20:18	15:25	8:35	17	28	0	28
2012 05 29	4:52	20:19	15:27	8:33	18	26	-2	24

Table 1. shows the data for each day, the day/night ratio, and the daytime and nighttime water level changes. There are days when the morning and evening condensation causes the water level to be negative. The smallest change in water level was 13.6 and the biggest was 42.6 mm. Average daily temperatures on spring days varied between 14 to 20 ° C, on summer days between 17 to 26 ° C and on autumn days between 16 to 24 ° C.

***Table 2.:** Daily, daytime and nighttime evapotranspiration values for days measured*

Date	Evapotranspiration (mm/day)	Evapotranspiration and maximum hydraulic loading rate ratio (%)	Evapotranspiration at day time (%)	Evapotranspiration at night time (%)	Daily condensation and maximum hydraulic load rate ratio (%)
2011 08 11	12,3	30,8	73,0	27,0	0,0
2011 08 27	42,3	105,8	71,7	28,3	0,0
2011 08 28	24,3	60,8	82,2	17,8	1,8

DOI: https://doi.org/10.14232/analecta.2020.2.1-12

2011 08 29	21,7	54,3	100	0	8,3
2011 08 30	21,7	54,3	90,8	9,2	5,8
2011 08 31	17,7	44,3	79,1	20,9	0,8
2011 09 11	22,7	56,8	100	0	5,8
2011 09 25	13,6	34,0	100	0	5,8
2011 09 27	13,7	34,3	100	0	5,8
2011 09 29	13,7	34,3	92,7	7,3	0,8
2012 05 18	18,0	45,0	100	0	4,3
2012 05 24	42,6	106,5	90,6	9,4	0,0
2012 05 25	30,4	76,0	93,1	6,9	0,0
2012 05 27	27,0	67,5	92,6	7,4	3,3
2012 05 28	28,0	70,0	100	0	3,3
2012 05 29	24,0	60,0	100	0	10,0

The daily evapotranspiration values and the degree of condensation were compared to the maximum hydraulic load, which is 40 mm / day for the horizontal sub-surface flow constructed wetlands, and the daytime and nighttime evapotranspiration were separated. The results of the calculations summarized in Table 2., lead to the following conclusions:

- On the days under investigation, 71.7-93.1% of the total daily amount evaporated during the daytime hours. It follows that the concentration processes caused by evapotranspiration were 4-10 times more potent during daytime than nighttime in this constructed wetland.
- The evapotranspiration at night is significant, as there are some days when the total, daily water loss via evapotranspiration is 21.0-28.0 % of the total daily water loss, these values are similar to Dittrich *et al.* [30].
- There were days when the condensation values were high, consequently, the daytime and nighttime ratio could not be divided.
- During the spring, the estimated evapotranspiration is 18.0-42.6 mm/day, which is 45.0 - 106.5 % of the maximum hydraulic load.
- During the summer, the estimated evapotranspiration is 12.3-42.3 mm/day, which is 30.8-105.8 % of the maximum hydraulic load.
- The estimated evapotranspiration in autumn is 13.6-22.7 mm/day, which is 34.0-56.8 % of the maximum hydraulic load**.**
- Days when there was measurable condensation in the constructed wetland, the value varied between 1.8 to 10.0 % of the daily maximum hydraulic load, this phenomenon was found to decrease the concentration in the CW, especially after sunrise.

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Analecta Technica Szegedinensia
Vol. 14, No. 2 ISSN 2064-7964 2020

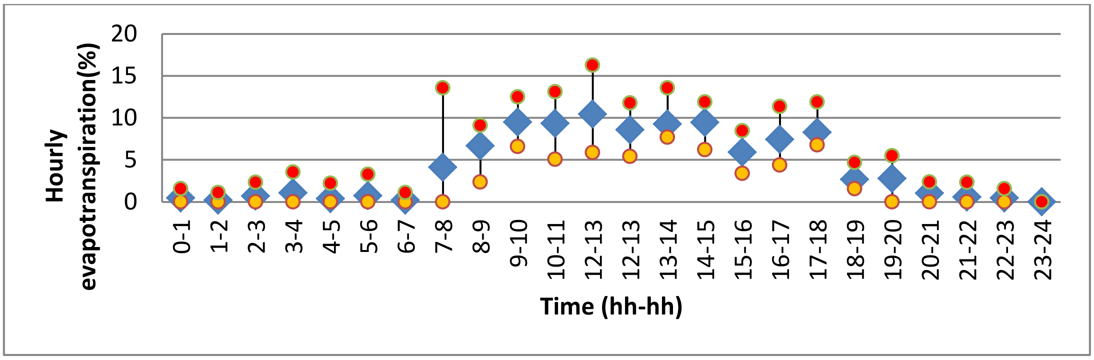

Figure 9.: Changes in the mean, minimum and maximum hourly evapotranspiration on spring days, expressed as a percentage of daily evapotranspiration

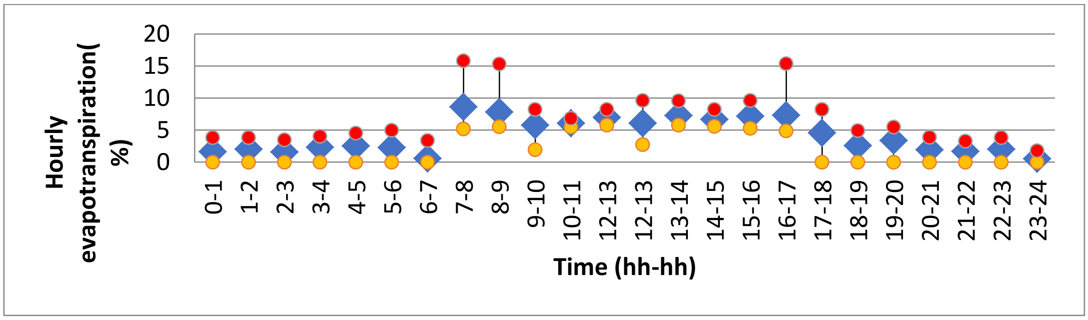

Figure 10.: Changes in the mean, minimum and maximum hourly evapotranspiration on summer days, expressed as a percentage of daily evapotranspiration

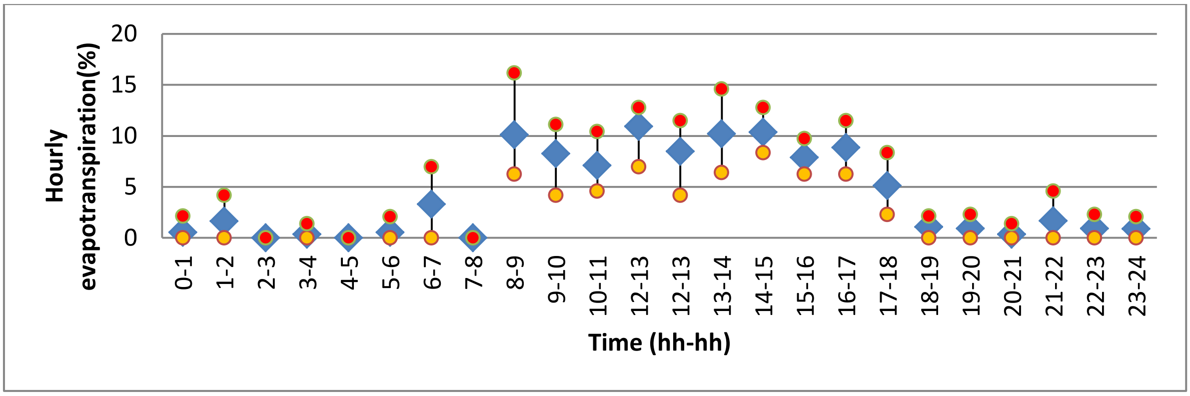

Figure 11.: Changes in the mean, minimum and maximum hourly evapotranspiration on autumn days, expressed as a percentage of daily evapotranspiration

Figures 9.-11. show changes in the mean, minimum and maximum hourly evapotranspiration rates in spring, summer and autumn, expressed as a percentage of daily evapotranspiration. The mean evapotranspiration is low at night and then gradually increases until sunrise when the evapotranspiration decreases due to the morning condensation and then increases after sunrise and reaches the mean maximum at 12 to 13 pm. and then gradually decrease. These results were similar to Galvao *et al.* [23]. There are

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days when the maximum amount of evapotranspiration is in the morning and then a gradual decrease is observable.
The Figure 9. shows that the peak spring hourly evapotranspiration was around 16.3 % of the daily evapotranspiration, this value was around 15.8 % in summer and 16.2 % in autumn. Estimating the maximum spring hourly evapotranspiration from 42.6 mm/day, this value is 6.94 mm/h, 415 % of the average hourly hydraulic load (1.7 mm/h) of the cw. In summer and autumn these values are 229 % and 150 % of the average hourly hydraulic load of the CW. From This result led to the conclusion that the concentration processes occurring during the spring and summer can be extremely significant.

4. CONCLUSIONS

We measured the hourly, daily and seasonal evapotranspiration of a horizontal sub-surface flow constructed wetland for four months. We found 16 days when there was no precipitation and there was no inlet or outlet affecting this constructed wetland, meaning that the only effect upon the water balance of this CW was the evapotranspiration.
On the days investigated, 71.7-93.1% of the total daily amount evaporated during the daytime hours. It follows that the concentration processes caused by evapotranspiration were 4-10 times more potent during daytime than nighttime in this constructed wetland. The evapotranspiration at night is significant, as there are some days when the total daily water loss via evapotranspiration is 21-28 % of the total daily water loss.
We measured the evapotranspiration under local climatic conditions: in springtime the values were between 18.0-42.6 mm/day which amounted to 45.0-106.5% of the maximum hydraulic load, in summertime 12.3-42.3 mm/day; these values are similar to results of Freedman *et al.* [12]. The values were 30.8-105.8% of the maximum hydraulic load. The values were 13.6-22.7 mm/day in autumn, which is 34.0-56.8% of the maximum hydraulic load. These values are similar to those of Dittrich *et al.* [30]
There were days when the morning and evening condensation were very high causing significant increase in water level. This has two consequences, on the one hand, condensed vapor increases the water level supplying the constructed wetland, on the other hand, due to humidity of around 100%, evapotranspiration is slightly reduced. There were some days when during the hour following the morning condensation the transmitters registered the highest hourly water loss. Further research is needed to explore this causes of this phenomenon.
There was a day in springtime when the peak hourly evapotranspiration was around 16% of the daily evapotranspiration. This value was 415 % of the average hourly hydraulic load of the CW. These values were 229 % and 150 % in summer and autumn. As a result, the concentration processes occurring during the summer may be extremely significant.
Our research results showed the daily evapotranspiration rates in three different seasons in horizontal subsurface constructed wetland, and the effect of the morning and evening condensation in Central Eastern European region.
In the future, we plan to conduct 24-hour on-site measurements at the same field site in order to clarify the evaporation transpiration ratio as a function of local climatic conditions. Based on these measurements, we expect to develop an environment-calibrated engineering model to better estimate system-level evapotranspiration processes and mechanisms.

ACKNOWLEDGEMENTS

We would like to thank the water and sewage management research team of the University of Pécs, Faculty of Engineering and Information Technology for their cooperation. The project was supported by the European Union, co-financed by the European Social Fund under grant agreement No. EFOP-3.6.1.-16-2016-00004. The research was financed by NKFIH in Hungary, within the framework of the 2020-4.1.1-TKP2020 3rd thematic programme of the University of Pécs.

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