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Evapotranspiration dynamics in aerated and non-aerated subsurface flow treatment wetlands

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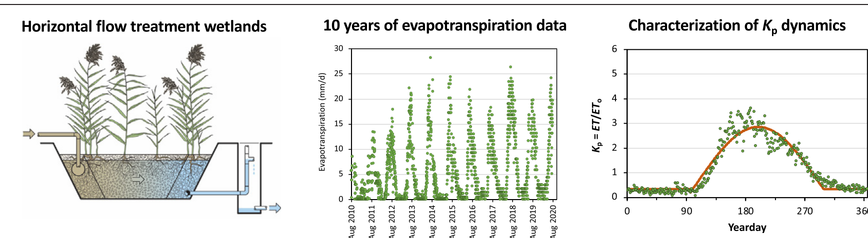
HIGHLIGHTS

- Evapotranspiration (*ET*) dynamics in saturated treatment wetlands are highly seasonal.
- *ET* loss in small wetlands is not appropriately described by a single value (K_p).
- K_p is characterized by sinusoidal equations which could be useful for modeling.
- A new Plant Scaling Factor (*PSF*) quantifies “clothesline effect” in small wetlands.

GRAPHICAL ABSTRACT



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ABSTRACT

This study reports the seasonal dynamics of evapotranspiration (*ET*) and evaporation (*E*) in different subsurface flow treatment wetlands operating in a temperate European climate. Daily water balances were compiled over the course of ten years (August 2010–July 2020). The study includes non-aerated horizontal flow wetlands (25 cm deep and 50 cm deep) as well as horizontal flow and vertical flow wetlands. The pilot systems were operated in planted and unplanted pairs, enabling *Phragmites* evapotranspiration rates (for planted systems) and evaporation rates (for unplanted systems) to be calculated. Evapotranspiration rates are highly seasonal. Aeration was observed to increase both evaporation and evapotranspiration rates. The overall percentage of inflow lost to *ET* was highest in non-aerated wetlands, due to the lower hydraulic load that they received compared to the aerated systems. Plant coefficients (K_p) relate measured evapotranspiration with the calculated reference evapotranspiration ET_o. Wetlands planted with *Phragmites* display dynamic and highly seasonal values of K_p which are well-characterized by a sinusoidal curve during the growing season paired with a minimum (stable) value in the non-growing season. Aeration was observed to increase both evapotranspiration and evaporation rates. The concept of a Plant Scaling Factor (*PSF*) is introduced as a way of quantifying the “clothesline effect” observed in small treatment wetlands. Whereas unplanted systems effectively have a *PSF* of zero, the systems in this study (ranging in size from 5.6 to 6.2 m^2) exhibited *PSF* values between 3.8 and 4.8 when the vegetation was fully mature.

1. Introduction

Subsurface flow treatment wetlands are nature-based technologies that are often used for decentralized treatment of wastewater, stormwater, or sewage sludge (Kadlec and Wallace, 2009). Subsurface flow wetlands typically treat higher-strength wastewater than treatment marshes (also referred to as free water surface wetlands) are generally smaller in size (Wallace and Knight, 2006). Outside of North America, where its use is generally prohibited, *Phragmites australis* is the most commonly used plant in subsurface flow treatment wetlands. Wetland vegetation provides a multitude of important functions, including, but not limited to thermal

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insulation, nutrient uptake, providing additional surface area for microbial growth, aesthetic value (Brix, 1997) as well as maintaining hydraulic conductivity in certain types of wetland systems (such as French vertical flow wetlands) (Lombard Latune et al., 2017).

Hydraulic functioning is a key component of subsurface flow treatment wetland design. Because subsurface flow treatment wetlands generally consist of a basin that is lined with an impermeable liner, the water balance is simplified. The main components of the water balance are the inflow, outflow, precipitation, and evapotranspiration. Evapotranspiration (*ET*) is the collective term for the following two processes of water loss from land surface to the atmosphere: Evaporation (*E*) is the process by which water is converted from liquid to vapor and removed from its source (soil, water body, etc.). Transpiration (*T*) is the vaporization and subsequent loss of water vapor through a plant. Evaporation and transpiration occur simultaneously and depend on local weather conditions such as solar radiation, air pressure, relative humidity, air temperature, and wind speed (Zotarelli et al., 2010). In small-scale treatment wetlands, *ET* is primarily driven by solar radiation and heat transfer from air and is often highly seasonal (Kadlec and Wallace, 2009). Water loss due to *ET* can significantly impact the water balance of a small-scale treatment wetland, consuming a significant portion of the inflow during the peak growing season (El Hamouri et al., 2007). Excessive water loss via *ET* can impact pollutant removal efficiency, due to the reduced wastewater volume in the outflow and concentration of pollutants in the system. In some cases, zero-discharge treatment systems (planted with *Salix* spp.) have been designed using *ET* as a primary dimensioning factor (Gregersen and Brix, 2001). The application of common methods for estimating *ET* to treatment wetlands is somewhat limited because there is a general lack of crop coefficients different wetland plants. Reported *ET* even for a relatively standard plant such as *Phragmites* varies widely depending on geographical location and climate.

This paper presents the results of ten years of results on the evapotranspiration by *Phragmites australis* in four pilot-scale subsurface flow treatment wetlands (and evaporation from four unplanted systems) at an outdoor research facility in Langenreichenbach, Germany. The objectives of this study were to (1) evaluate the dynamics of evapotranspiration and evaporation in aerated and non-aerated treatment wetlands; (2) characterize the plant coefficient K_p for *Phragmites australis*; and (3) develop a metric to quantify the "clothesline effect" in small-scale treatment wetlands and to explain why it is important to consider in design.

2. Materials and methods

The study was conducted at a research facility in Langenreichenbach, Germany (51.5°N, 12.9°E). The site is described in detail in Nivala et al. (2013). The site is comprised of 15 individual subsurface flow treatment wetlands (Fig. 1). This study reports data on eight systems: 50-cm deep horizontal flow wetlands (H50 and H50p), 25-cm deep horizontal flow wetlands (H25 and H25p), and aerated horizontal flow wetlands (HA and HAp), and aerated vertical flow wetlands (VAp and VA). The main filter media in all systems was 8–16 mm gravel. A summary of the physical attributes of systems in this study is shown in Table 1. Further details about the site can be found in Nivala et al. (2013). All systems were built in unplanted and planted pairs. Planted systems are designated with a "p" in the system abbreviation. *Phragmites australis* was planted in the vegetated systems in September 2009 at a density of five plants per square meter. The wetlands have been dosed with wastewater from June 2010 onwards. The treatment systems have been regularly monitored from August 1, 2010, through July 31, 2020, except for H25 and H25p, which were decommissioned in July 2014.

Wastewater received primary treatment in a sedimentation tank (nominal Hydraulic Retention Time (HRT) of two days). The tank was equipped with two commercial-size septic tank filters (Zoeller, screen size 0.8 mm). Wastewater was delivered to the wetlands by two submersible pumps, which pumped wastewater through the main control building. Horizontal flow systems were dosed every 30 min. Vertical flow systems once per hour. Inflow was dosed to each system via a series of pneumatic valves

Fig. 1. Photo of the research facility in Langenreichenbach, Germany.
Photo credit: André Künzelmann, UFZ.

Table 1
Treatment wetland systems in this study.

Systems[a]	Daily inflow (m^3/d)	Length × width (m)	Surface area (m^2)	Saturated depth (m)	Years of data
H25p and H25	0.1	4.7 × 1.2	5.6	0.25	4
H50p and H50	0.2	4.7 × 1.2	5.6	0.50	10
HAp[b] and HA[c]	0.6–0.7	4.7 × 1.2	5.6	1.00	10
VAp and VA[c]	0.6	2.4 × 2.75	6.2	0.85	10

[a] Planted systems are designated with a "p" in the abbreviation.
[b] Systems were aerated continuously (24 h/d).
[c] Systems were aerated continuously (24 h/d) except for periods where special experiments were conducted (see Table S1, (Boog et al., 2014; Boog et al., 2016; Boog et al., 2018; Boog et al., 2019; Sossalla et al., 2020)).

controlled by a programmable logic control (PLC) system. Inflow rates were measured by an electromagnetic flow meter and subsequently recorded by a central control computer. The outflow from each wetland system was measured by counting the number of times a calibrated vessel (Rotring SCS, Bremen, Germany) filled and emptied each hour. Outflow vessel volume was calibrated regularly, at least once per year, to an accuracy of 0.1 L. All data was recorded by a PLC system. Inflow was recorded with a magnet inductive flow meter (Endress+Hauser, Promag 10) and outflow was measured with a tipping counter. The research facility was equipped with an onsite weather station that measures air temperature, relative humidity, rainfall, air pressure, wind speed and direction, and solar radiation. Measurements were collected every 10 min (600 s). Weather data and flow measurements are from August 1, 2010–July 31, 2020.

2.1. Calculation of evapotranspiration (ET) and evaporation (E)

The calculation of evapotranspiration and evaporation was conducted based on a simplified water balance (Eq. (1)) using daily inflow and outflow measurements for each individual wetland system.

$$ET(\text{or } E) = \frac{(Q_{\text{in}} - Q_{\text{out}})}{A} \tag{1}$$

ET or E = m^3 of water loss per m^2 of wetland (mm/d)
Q_{in} = inflow (L/d)
Q_{out} = outflow (L/d)
A = wetland area (m^2)

Flow data from days of operations and maintenance, where wetlands received less than design flow or no flow at all were removed from the analysis, as they were not representative of steady-state flow conditions (e.g., falsely elevated water loss). Removing all days with precipitation resulted in a large amount of data exclusion (36 % of daily records). As a compromise, days with precipitation events >4 mm in one day or >10 mm in two days were removed from analysis (accounting for 11 % of daily records) since heavy precipitation on these days resulted in an overall water gain.

2.2. Calculation of reference evapotranspiration ET_o

ET can be estimated using a variety of methods, the most common of which are Penman (1948) Penman-Monteith (Monteith, 1965) as presented in Allen et al. (1998), FAO-56 Method (Allen et al., 1998; Zotarelli et al., 2010), and the ASCE-EWRI Method (Walter et al., 2001). Reference evapotranspiration (ET_o) is the evapotranspiration from a uniform surface of dense, actively growing grass with an expanse of at least 100 m. The concept of ET_o was developed to calculate evaporative demand of the atmosphere independent of the type of vegetation or crop.

ET_o is calculated solely from climate data. When climate data is measured in short time intervals (t), ET_o can be calculated according to Eqs. (2) and (3) (DVWK, 1996). In this analysis, t was 600 s and L^* was 2,449,000 W s/kg. The units on the factor 1.08 are in s/m and the units on the conversion factor 37.6 are in W/m^2. Eqs. (2) and (3) were used to calculate ET_o from the weather data collected at the research site in Langenreichenbach. Data collected every 10 min produced average ET_o values over a 10-minute interval. These data were subsequently used to calculate average daily mean ET_o.

$$ET_o = g(T) \times \frac{t}{L^*} \times (0.6 \times R_G + 37.6 \times (1 + 1.08 \times v_2)) \times \left(1 - \frac{U}{100}\right) \tag{2}$$

$$g(T) \approx 2.3 \times \left(\frac{T + 22}{T + 123}\right) \tag{3}$$

where: t = time interval between measurements, in seconds
R_G = global radiation, W/m^2 (average over time interval t)
L^* = specific heat of evaporation, W·s/kg
T = air temperature in °C (average over time interval t)
v_2 = wind speed at 2 m height, m/s (average over time interval t)
U = relative humidity in percent (average over time interval t)

2.3. Calculation of the plant coefficient K_p

In large wetlands, ET can be estimated by ET_o. Small wetlands (e.g., surface area of <1 ha) exhibit amplified ET rates because they have significantly greater convective heat transfer than large wetlands. This results in an actual ET that is much larger than the ET_o potential ET_o calculated from weather data. The plant coefficient K_p is analogous to the FAO crop coefficient (K_c) and represents the ratio of the observed ET to the potential ET_o (Eq. (4)) (Fermor et al., 2001). Plant coefficients greater than one indicate an actual ET greater than the ET_o predicted from the energy balance. Unplanted systems will not exhibit ET losses but may lose water through evaporation. To determine the plant coefficient K_p, Eq. (4) can be reorganized (Eq. (5)).

$$ET = K_p \times ET_o \tag{4}$$

$$K_p = \frac{ET}{ET_o} \tag{5}$$

where: K_p = plant coefficient, dimensionless
ET = observed evapotranspiration, mm/d
ET_o = reference evapotranspiration, mm/d

K_p is a dynamic coefficient that changes over time. For the growing season ($t_1 < t < t_2$), this can be described by Eq. (6) and for the rest of the year ($t_1 < t < t_2$) by Eq. (7). Due to the symmetry of the cosine curve around t_{max}, the relationship between t_1 and t_2 is represented by Eq. (8). The resulting dynamics of K_p are visually presented in Fig. 2.

$$K_p = K_{p,\text{mean}} \times (1 + A \cdot \cos[\omega(t - t_{\max})]) \tag{6}$$

$$K_p = K_{p,\ \min} \tag{7}$$

$$(t_{\max} - t_1) = (t_2 - t_{\max}) \tag{8}$$

where: t = time, Julian yearday
K_p = plant coefficient, unitless
$K_{p,\ mean}$ = mean plant coefficient for the sinusoidal portion of the time series, unitless

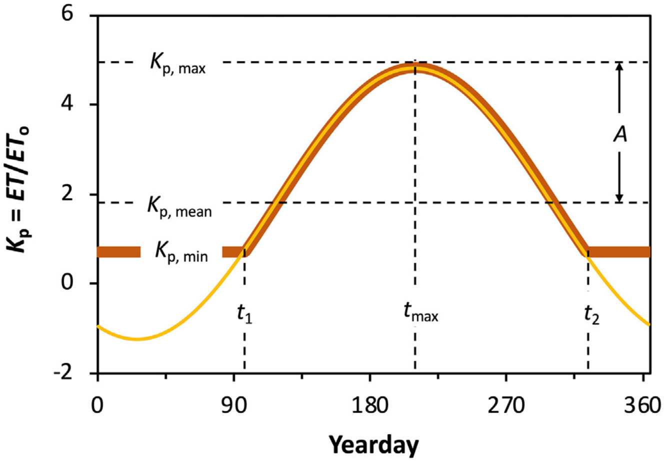

Fig. 2. Conceptual visualization of the changes in K_p over time (northern hemisphere assumed).

$K_{p,\,min}$ = minimum plant coefficient for the flat portion of the time series, unitless
A = amplitude of the cosine curve, unitless
ω = yearly cycle frequency, $= 2\pi/365 = 0.01721\ d^{-1}$
t_{max} = time of peak annual maximum K_p, Julian yearday
t_1 = start of growing season, Julian yearday
t_2 = end of growing season, Julian yearday

2.4. Calculation of the plant scaling factor

Evapotranspiration (*ET*) is typically reported using reference evapotranspiration (ET_o) as a baseline with a plant coefficient K_p as a multiplier. One major component of this variability is the influence of the "clothesline effect" on *ET*, where the vegetation height is greater than that of the immediate surroundings, resulting in inflated evapotranspiration rates.

Wind and solar radiation, which are major influencing mechanisms of *ET*, play a larger role in the water balance of small systems when the perimeter area of the wetland is large relative to the wetland area (Fig. 3). Plants impose their own scale factor, independent of the footprint area of the system they are planted in. As a result, plants have a larger influence the smaller the wetland area is, or the taller the vegetation grows (Fig. 3). One means of assessing this is to calculate a Plant Scaling Factor (*PSF*), which can be defined as:

$$PSF = \left(\frac{2(L+W)\times h_{plant}}{A}\right)\times\left(\frac{\text{plant stem density}}{\text{maximum plant stem density}}\right) \tag{9}$$

where: L = wetland length, m
W = wetland width, m
h_{plant} = plant height, m
A = wetland area, m^2

If the $PSF \leq 0.1$, then the "clothesline effect" is minimal because the wetland area is much larger than the effective perimeter area imposed by the vegetation. Consequently, the system will likely represent the role of vegetation in a representative way. As the perimeter area (perimeter length × plant height) increases relative to the wetland area, the more pronounced the "clothesline effect" becomes. This is supported by the observation that studies on small wetland systems lead to inflated estimates of *ET* (Idso and Anderson, 1988; Abtew and Melesse, 2013). In some wetland systems, particularly aerated systems, it can take years for vegetation to become fully established, hence, the *PSF* can be back calculated during the startup phase if the final density of plant stems is known.

In this study, some systems were unplanted (H25, H50, HA and VA), rendering a *PSF* of essentially zero, meaning that any potential "clothesline effect" in these unplanted wetlands is minimal. The vegetated systems H25p, H50p, HAp and VAp experienced establishment periods of variable duration (more than one growing season) until mature plant stands were established (Table 2).

Stem density was quantitatively measured in 2010 and 2011 by counting all stems in a representative transection of each wetland (Nivala, 2012), and thereafter qualitatively estimated as percentage of cover. In 2010, each horizontal flow bed was divided into four quarters, and a representative 20 cm section within each quarter was delineated (0.2 m wide by 1.2 m long) in order to account for spatial heterogeneity of plant growth in these beds. The 2010 aboveground biomass measurements occurred on

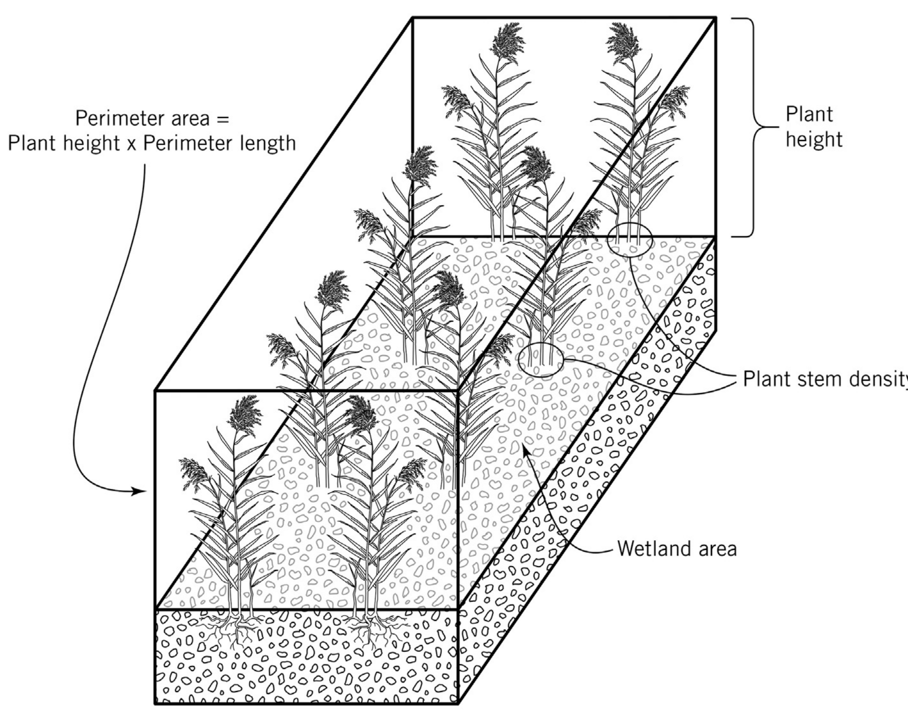

Fig. 3. Illustration of perimeter area (perimeter length x plant height) relative to wetland area.

Table 2
Data used to calculate the Plant Scaling Factor.

	2010	2011	2012[a]	2013–2014[a]	2015–2020[a]
Mean plant height (cm)					
H25p	79	112	150	200	–
H50p	83	113	150	200	200
HAp	55	88	170	200	230
VAp	27	106	145	230	230
Plant stem density (stems/m^2)					
H25p	79	87	90	90	–
H50p	86	71	90	90	90
HAp	48	76	75	81	90
VAp	6	22	54	64	90

[a] Estimated based on observations and a maximum observed stem density of 90 stems/m^2 in 2011.

29–30 September 2010. The stems within the delineated section were counted according to height class; twine wrapped around the rods at each corner of a section was used to designate each 20 cm-height increment. In 2011, the plants were too dense to use the non-destructive method, so 20-cm wide sections were harvested in order to estimate shoot density and biomass. The plants were cut at the gravel surface, sorted into 20-cm increment height classes, and counted. The 2011 aboveground biomass measurements took place on 28–29 September 2011. A general maximum stem density was estimated to be 90 stems/m^2, based on the density of 87 stems/m^2 observed in H25p in 2011. Plant height was also quantitatively measured in 2010 and 2011, and thereafter estimated using photo documentation. Photos of plant establishment are provided in the Supplementary Information (Figs. S2, S3, S4, and S5).

3. Results and discussion

3.1. Environmental conditions

Relative humidity, air temperature, wind speed, air pressure, and solar radiation data were collected every 10 min from the onsite weather station. These data were used to calculate daily mean values as well as the mean daily reference Penman evapotranspiration ET_o (Fig. 4). Air temperatures at the site displayed a seasonal, sinusoidal pattern, with daily mean temperatures in winter reaching as low as −15 °C and peak summertime temperatures of +30 °C. Solar radiation is the dominating factor in the calculation of the reference Penman evapotranspiration ET_o.

The weather station at the research site in Langenreichenbach was situated above the main control building (gray building, center of Fig. 1), was

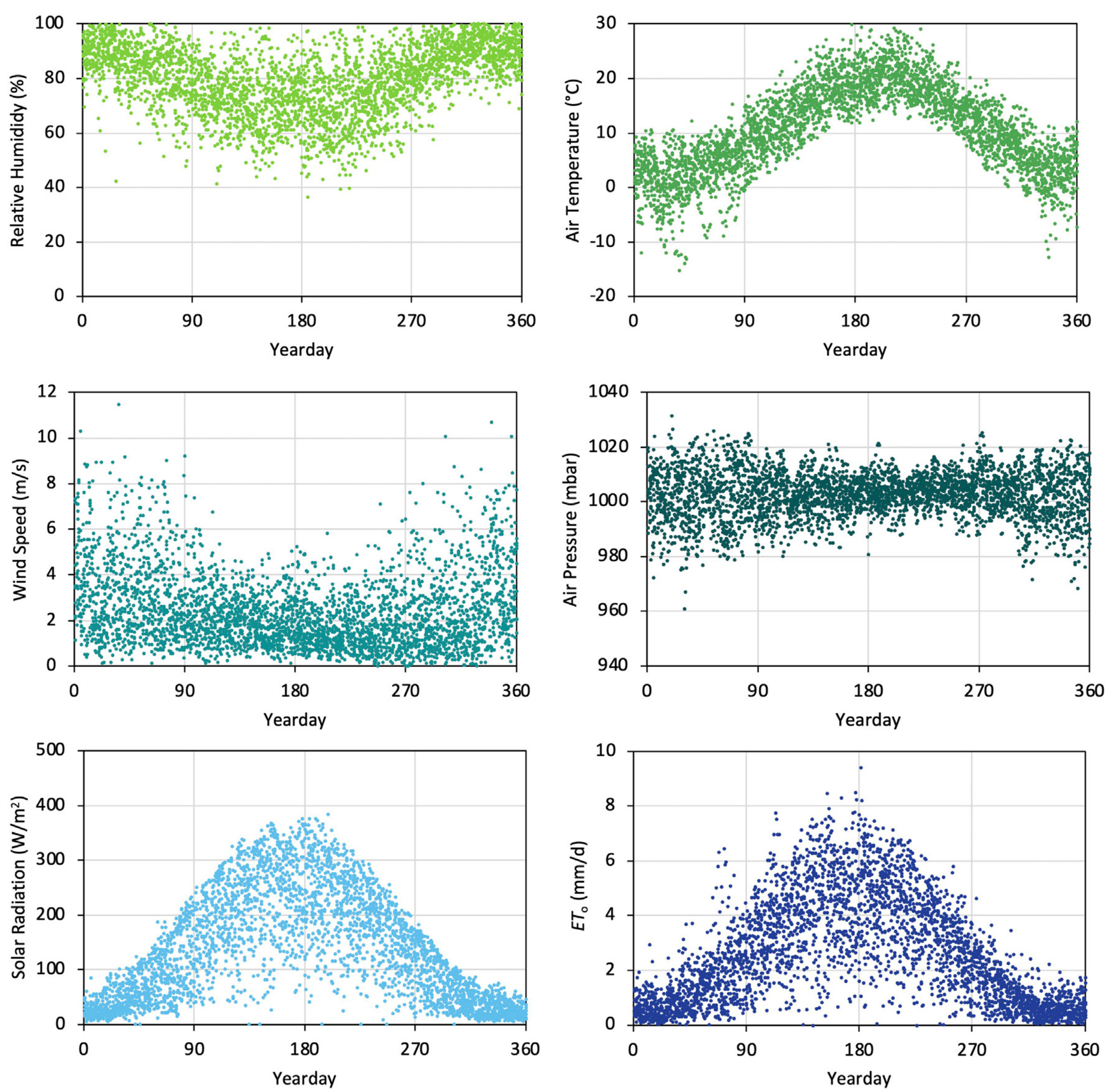

Fig. 4. Daily mean relative humidity, air temperature, wind speed, air pressure, solar radiation, and calculated Penman evapotranspiration (ET_o) at the research platform in Langenreichenbach, Germany. Data shown are from August 2010–July 2020.

elevated compared to the surrounding land. Reference evapotranspiration rates calculated from the weather data at the research site in Langenreichenbach were more variable and approximately 20 % higher than those calculated from the nearest weather station in Klitzchen, Germany, which is located approximately 4 km from the research site (see Fig. S1), presumably due to the elevated nature of the research site, which stands approximately three meters higher than the surrounding agricultural fields, and is thus prone to higher ET losses due to wind effects.

3.2. Evaporation and evapotranspiration

The daily evaporation and evapotranspiration rates for each system are shown in Fig. 5. The presence of vegetation is the single largest factor in water losses, with *ET* being considerably higher than non-vegetated systems (*E*) at the height of the growing season when net solar radiation is near maximum and air temperatures are warm (Fig. 5). This seasonality effect is linked to climate and latitude (51.5°N). Evapotranspiration rates in

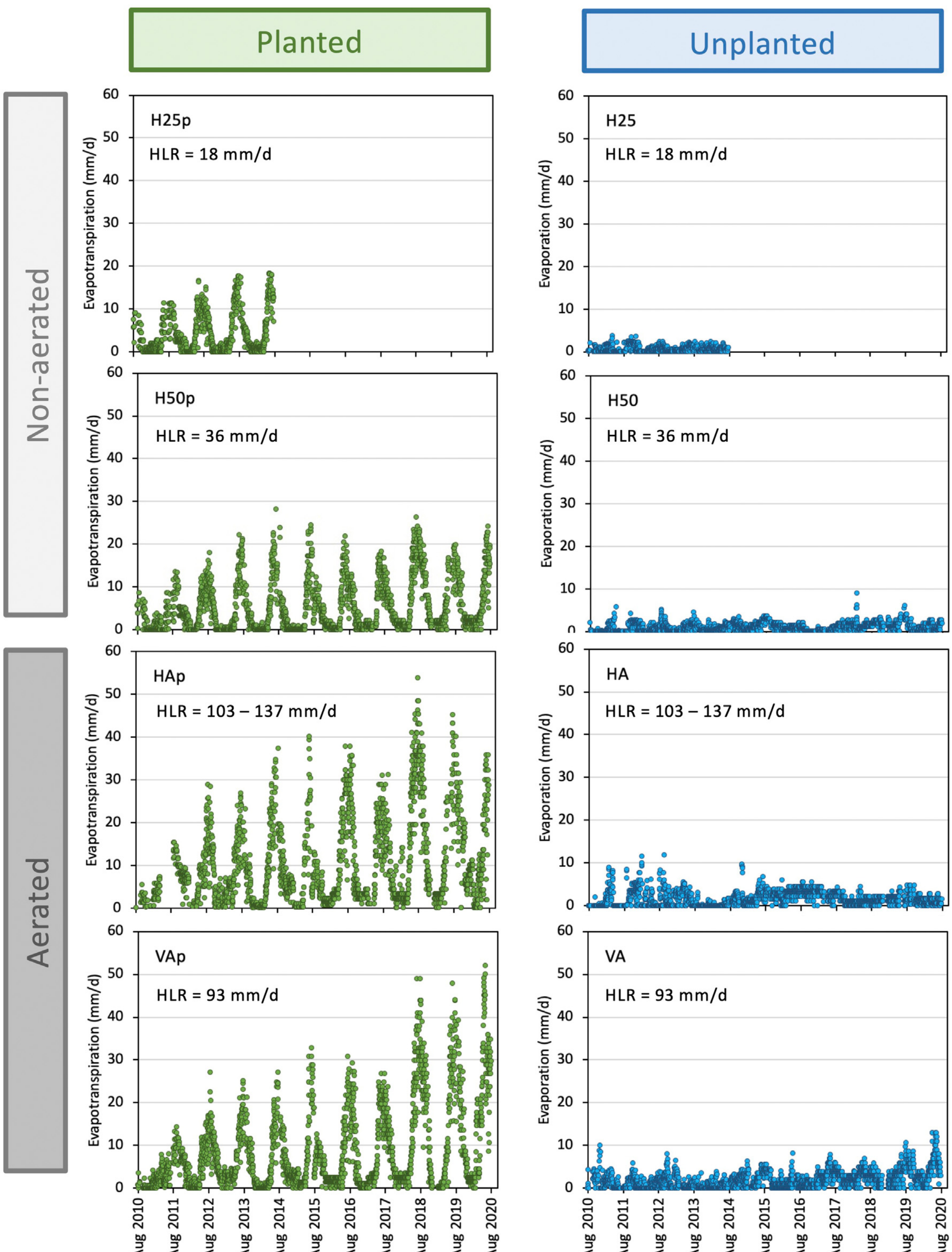

Fig. 5. Daily evapotranspiration and evaporation rates for the eight systems.

Table 3
Mean daily and maximum daily evaporation and evapotranspiration rates.

System	Mean daily *E* or *ET* (mm/d)	Maximum daily *E* or *ET* (mm/d)
H25	1.0	3.8
H50	1.4	6.2
HA	2.2	11.8
VA	2.6	12.9
H25p	4.9	18.2
H50p	6.3	28.2
HAp	10.8	53.8
VAp	9.2	52.0

the non-aerated wetlands H50p and H25p plateaued after the third full growing season. H50p exhibited a mean daily ET of 6.3 mm/d over the course of the study (maximum daily $ET = 28.2$ mm/d). H25p exhibited a mean daily ET of 4.9 mm/d over the course of the study (maximum daily $ET = 18.2$ mm/d) (Table 3). The aerated, planted wetlands HAp and VAp exhibited higher *ET* rates (10-year mean values of 10.8 mm/d and 9.2 mm/d, respectively) and the vegetation took more growing seasons to become fully established (Fig. 5). Maximum observed daily *ET* rates for HAp and VAp were 53.8 mm/d and 52.0 mm/d, respectively.

Mean daily evaporation rates in the non-aerated wetlands H50 and H25 were low (1.0–1.4 mm/d, Table 3). Evaporation rates in the aerated wetlands HA and VA were higher, with mean values of 2.2 mm/d and 2.6 mm/d, respectively. Maximum evaporation rates for the non-planted aerated wetlands ranged from 11.8 mm/d (HA) to 12.9 mm/d (VA). The aeration system may increase water losses due to several factors. Aeration creates a considerable degree of mixing within the water column as demonstrated by lower number of Tanks-in-Series (NTIS) values compared to non-aerated wetlands (Boog et al., 2014), especially for the saturated vertical flow systems VA and VAp. The counteractive movement of influent wastewater dosing (downward) and air bubbles rising (upward) prevents thermal stratification and increases thermal and gas exchanges at the air/water interface. This is suspected lead to increased evaporation, especially if the air has a low relative humidity.

Aerated wetlands exhibited higher *ET* losses than the non-aerated wetlands. However, when *ET* is related to the total percentage of inflow lost, it is highest in non-aerated wetlands (Fig. 6). Maximum *ET* rates for H25p often reached the influent hydraulic loading rate of the system, resulting in zero outflow in peak summer season (Fig. 6). Up to 80 % of incoming wastewater for H50p was lost to evapotranspiration. This high percentage of water loss is because the hydraulic load of non-aerated wetlands (0.1–0.2 m^3/d) is much lower than that of the aerated wetlands (0.6–0.7 m^3/d) (Fig. 6, Table 1). Headley et al. (2012) report a lower percentage of inflow lost to *ET* for horizontal flow wetlands located in a tropical climate on the east coast of Australia (mean monthly percent loss of 5–27 %). The mean daily values for the non-aerated wetlands are in the range reported in other studies. Burba et al. (1999) report a daily mean *ET* for *Phragmites australis* of 3.8 mm/d in Nebraska, USA (42°30′N, 100°25′W), whereas El Hamouri et al. (2007) report an average *ET* of 57 mm/d from a horizontal flow treatment wetland located in the northwest of Morocco (30°03′N, 16°46′W).

While wetland aeration is typically considered to be a process to increase dissolved oxygen in the water column, it is important to note that diffusion at the air/water interface of the bubble is a two-way process. As oxygen diffuses out of the air bubble, other gases, such as water vapor, can diffuse in. The transit of air bubbles through the porous media of a subsurface flow wetland is characterized by tortuous flow paths and bubble retardation (Butterworth, 2014). If the compressed air introduced into the wetland is dry (low relative humidity), this creates conditions favorable for water evaporation into the air bubbles.

3.3. Plant coefficients (K_p) and evaporation losses (E/ET_o)

Studies on evapotranspiration in treatment wetlands often report an annual or growing season values of K_p (Snyder and Boyd, 1987; Herbst and Kappen, 1999). Reported annual mean K_p values for *Phragmites* in non-aerated wetlands varies widely in the literature, from 0.71 (Zhou and Zhou, 2009) to 7.0 (Borin et al., 2011). The wide variability in reported K_p values is likely due to differences in the size of the system studied in relation to the size and density of the *Phragmites*. As mentioned earlier, *ET* in small treatment wetland systems is often much higher than reference ET_o rates because the plants impose their own scaling factor, independent of the area of the system in which they are planted. As a result, the smaller the wetland area is, or the taller the vegetation grows, the larger is the influence of plants on observed *ET*. This can be described by the Plant Scaling Factor, which is presented in more detail in the next section.

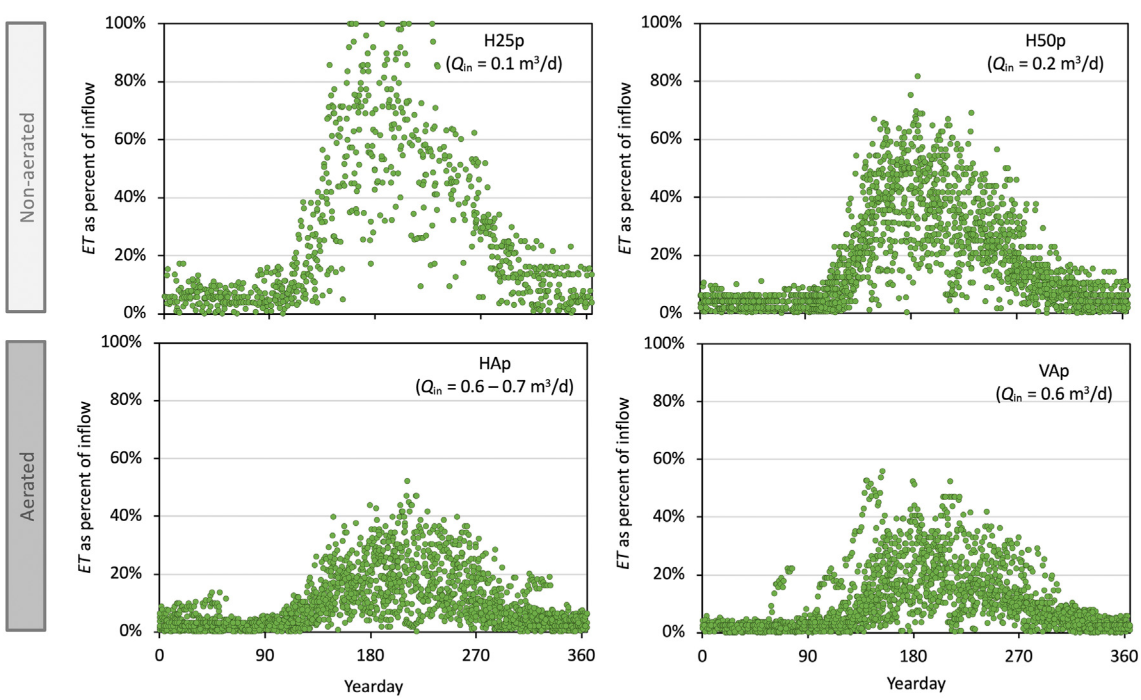

Fig. 6. Daily evapotranspiration rates presented as percent of daily inflow.

Table 4
Relative impact of vegetation on water loss coefficients.

Year	K_p (planted systems)				E/ET_o (unplanted systems)			
	H25p	H50p	HAp	VAp	H25	H50	HA	VA
2011	0.8	0.8	1.5	0.9	0.3	0.3	0.7	0.4
2012	1.1	1.3	1.9	1.4	0.2	0.2	0.6	0.4
2013	1.1	1.6	1.6	1.4	0.2	0.2	0.5	0.3
2014	1.1[a]	1.3	2.0	1.4	0.2[a]	0.2	0.4	0.3
2015	–	1.2	1.5	1.2	–	0.3	0.4	0.5
2016	–	1.2	2.3	1.5	–	0.2	0.6	0.3
2017	–	1.3	2.3	1.8	–	0.4	0.5	0.7
2018	–	2.0	3.6	3.2	–	0.4	0.3	0.6
2019	–	1.2	2.6	2.9	–	0.4	0.4	0.7
2020	–	1.6	2.4	3.9	–	0.3	0.2	1.0
10-year mean	1.0	1.3	2.2	2.0	0.2	0.3	0.5	0.5

[a] January through July only.

The annual mean and 10-year mean K_p values for this study are presented in Table 4. The data shows that the non-aerated wetlands H25p and H25 reached an established *Phragmites* stand after the first growing season. The aerated wetlands HAp and VAp did not reach steady-state plant density until much later. Evaporative water losses, as described by E/ET_o, were approximately twice as high in the aerated systems, compared to their non-aerated counterparts.

Monthly reports of K_p dynamics treatment wetlands are uncommon. One study reports monthly K_p for three reed bed systems in the UK, ranging between 0.46 and 2.10 (Fermor et al., 2001). Headley et al. (2012), who reported monthly mean K_p values ranging between 1.3 and 6.0 for horizontal flow treatment wetland systems on the eastern coast of Australia (28.95°S, 153.46°E).

The data collected in this study were summarized on a daily basis and reveal that evapotranspiration (ET) and K_p display considerable variation

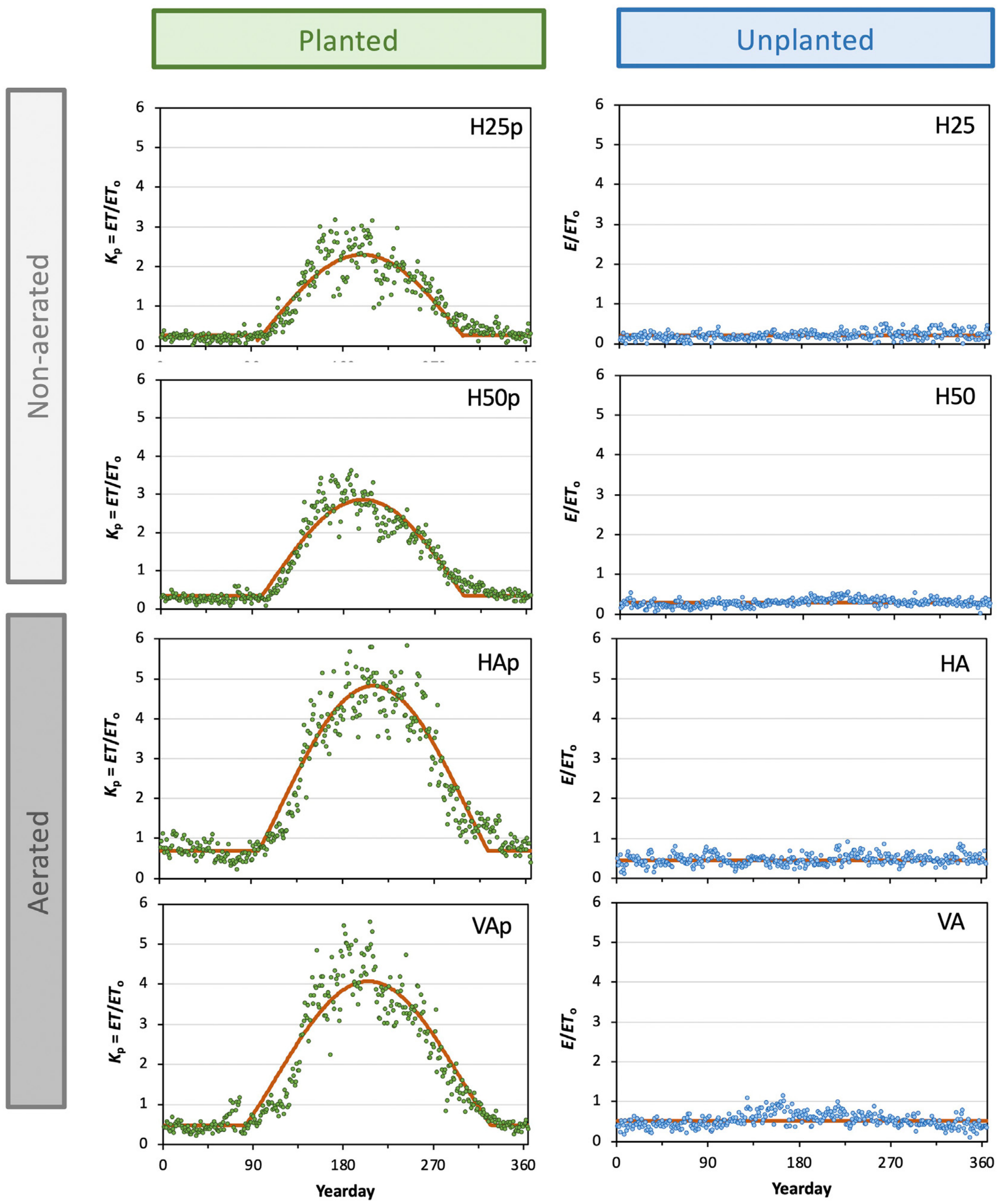

Fig. 7. Summary of daily *Phragmites* plant coefficients (K_p) for four planted treatment wetland systems and water loss factors (E/ET_o) for four unplanted systems.

Table 5
Characteristics of best-fit cosine curves for the daily mean K_p data.

System	$K_{p,min}$	$K_{p,mean}$[a]	A	t_{max} (Julian day)	t_1 (Julian day)	t_2 (Julian day)	Coefficient of determination
H25p	0.3	0.5	3.6	199	95	299	0.82
H50p	0.3	0.7	3.4	199	95	299	0.92
HAp	0.7	1.8	1.7	210	97	323	0.91
VAp	0.5	1.7	1.4	205	80	328	0.90

[a] $K_{p,mean}$ represents the mean of the sinusoidal portion of the curve only, not of the full year.

over the course of a year. The patterns observed reveal an annual cycle that can be described by a sinusoidal pattern during the growing season and a constant minimum value ($K_{p,min}$) during the rest of the year (Fig. 7, Table 5). The best-fit curves and $K_{p,min}$ values resulted in good correlations (CoD > 0.8) for the four planted systems. Incorporating water loss improves first-order models that describe pollutant removal in saturated treatment wetlands (von Sperling and de Paoli, 2013). The equations presented in this study could be used to account for water loss in these models and improve their accuracy.

3.4. Application of K_p and the Plant Scaling Factor (PSF) in design

Water losses through evaporation and evapotranspiration can be linked to normalized water loss coefficients (E/ET_o and K_p) for non-vegetated and vegetated systems, respectively. These water loss coefficients are also influenced by the scale factor of the wetland vegetation relative to the overall wetland area, as summarized by the plant perimeter scaling factor, or *PSF* (Table 6).

The utility of the *PSF* as a design tool is to either maximize or minimize the plant coefficient, K_p. Some wetland designs such as willow-based zero-discharge systems are designed specifically to maximize K_p and associated evapotranspirative losses, primary through length-width configurations that maximize the *PSF*. When interpreting data from small-scale systems, it is important to realize that evapotranspiration losses may not be representative of larger treatment wetlands, again due to the factors that contribute to the *PSF*.

4. Conclusions

This study reports 10 years of evaporation and evapotranspiration rates for pilot-scale aerated and non-aerated treatment wetland systems. Major factors that contribute to the variability and the overall magnitude of water losses in treatment wetlands include the presence of vegetation, fluctuations in annual weather patterns, time required for full plant establishment, and as revealed in this study, the presence of aeration. This study demonstrates the strong seasonal dynamics of evapotranspiration in planted treatment wetlands, which is an important aspect that should be considered in the design of small-scale treatment wetland systems. These results may facilitate technology selection because as absolute *ET* water losses increase, the water quality of treated water decreases, potentially limiting its potential for reuse. However, downstream treatment steps such as soil infiltration, would benefit from lower volumes of effluent disposal.

Table 6
Calculated Plant Scaling Factors for the four planted wetlands.

	2010	2011	2012[a]	2013–2014[a]	2015–2020[a]
H25p	1.5	2.3	3.1	4.2	–
H50p	1.7	1.9	3.1	4.2	4.2
HAp	0.6	1.6	2.8	3.8	4.8
VAp	0.0	0.5	1.4	3.1	3.8

[a] Estimated based on observations and a maximum measured stem density of 90 stems/m^2

Small-scale treatment wetland systems, such as the ones in this study (5–6 m^2) are subject to increased evapotranspiration due to the "clothesline effect", which has been quantified for the first time in this paper as the Plant Scaling Factor (*PSF*). The planted, non-aerated wetlands H25p and H50p reached mature *Phragmites* stem height and vegetation density faster than the aerated wetlands HAp and VAp (non-aerated wetlands reaching peak density in three growing seasons as opposed to five for the aerated wetlands). The 25-cm deep horizontal flow treatment wetland (H25p) lost up to 100 % of the daily inflow to evapotranspiration in peak warm weather. Aeration was observed to increase both evapotranspiration and evaporation in treatment wetlands because interactions between the air bubbles and water column create additional evaporation mechanisms.

The cosine fit of K_p in this study are based on 10 years of operational data, providing a simple estimation of the overall water loss in saturated treatment wetland systems. Incorporating water loss improves models that describe treatment wetland performance (von Sperling and de Paoli, 2013). The outcomes of this study could be integrated into future wetland models in order to better characterize the hydrodynamics evapotranspiration losses of different wetland designs. Future studies should focus on treatment wetlands in climates other than temperate climates to enable improved understanding and dimensioning of treatment wetlands worldwide. If biomass harvesting is conducted, the time of harvest (e.g., month) and frequency (e.g., annual) should be noted in figure studies, as well as the aboveground dry biomass in kg/m^2·d.

CRediT authorship contribution statement

J. Nivala: Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **S. Wallace**: Methodology, Validation, Formal analysis, Investigation, Writing - review & editing. **M. van Afferden**: Methodology, Writing - review & editing, Supervision, Resources. **R.A. Mueller**: Writing - review & editing, Supervision, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.156605.

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