Evapotranspiration and crop coefficient for *Typha latifolia* in constructed wetlands

João Gabriel Thomaz Queluz, Francisca Franciana Sousa Pereira and Rodrigo Máximo Sánchez-Román

ABSTRACT

The purpose of this work was to estimate the crop evapotranspiration (ETc) and to determine the crop coefficient (Kc) of *Typha latifolia* in constructed wetlands. The experiment used two horizontal subsurface flow constructed wetlands (HFCWs) cultivated with *T. latifolia*. Each HFCW received 50 L of secondary effluent daily, resulting in 3.2 days of nominal hydraulic retention time (disregarding effects of evapotranspiration and precipitation). In order to determine the ETc, water mass balance of the HFCWs was performed. In this analysis, ETc was considered equal to the difference between the inflow (secondary effluent + precipitation) and the outflow. The Kc was calculated using ETc and reference evapotranspiration (ETo) data (Kc = ETc/ETo). The results showed that 7-day average ETc varied dramatically within the range of 4.9–20.0 mm day^{-1}, with an monthly average of 9.85 mm day^{-1}. The mean monthly values of Kc varied from 2.03 to 3.68 (mean: 2.74). ETc is very important with respect to the HFCW water balance because it decreases effluent outflow considerably. Therefore, the findings of this work indicate that water losses caused by evapotranspiration should be considered when designing constructed wetlands.

Key words | constructed wetlands, crop coefficient, evapotranspiration, *Typha latifolia*, wastewater, water balance

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INTRODUCTION

Most domestic wastewater treatment systems are complex. Their construction and maintenance costs are high and their operation requires high levels of training. Thus, implementing such systems in rural, low-income communities can be impractical. Rural areas need systems that are inexpensive, simple, and easy to operate. These characteristics are typically found in ecotechnologies, particularly horizontal subsurface flow constructed wetlands (HFCWs).

The HFCW treatment process is highly efficient at removing total suspended solids and reducing biochemical oxygen demand, chemical oxygen demand, and pathogens (Abou-Elela *et al.* 2013; Weerakoon *et al.* 2013; Çakir *et al.* 2015; Toscano *et al.* 2015; Vergeles *et al.* 2015; Carballeira *et al.* 2016). However, the efficiencies of such systems change with the hydrological cycle. For this reason, rainfall and water losses due to crop evapotranspiration (ETc) should be considered when designing HFCWs (USEPA 1995; Brasil & Matos 2008). However, including ETc as a design factor can be complicated. In particular, there are discrepancies in the values found in the literature because environmental conditions and different methods used for determining evapotranspiration can affect the results (Goulden *et al.* 2007). It should be noted that even though there are several methods widely used to determine ETc, there is no consensus regarding the most appropriate methodology (Mohamed *et al.* 2012).

One of the principal methods for determining ETc uses the product of the reference evapotranspiration (ETo) and

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the crop coefficient (Kc). However, calculating the appropriate value of Kc is also complicated. First, the value of Kc depends on the macrophyte species used. The literature describes how HFCWs are cultivated using various macrophytes, that among others, include *Bassia indica*, *Cyperus alternifolius*, *Iris pseudacorus*, *Juncus effusus*, *Phragmites australis*, *Schoenoplectus fluviatilis*, *Typha angustifolia*, *Typha latifolia*, and *Vetiveria zizanioides* (Lim *et al.* 2001; Headley *et al.* 2012; Leto *et al.* 2013; Beede *et al.* 2014; Freedman *et al.* 2014; Tunçsiper *et al.* 2015; Carballeira *et al.* 2016; Bakhshoodeh *et al.* 2017). Finally, similar to the determination of ETc values, Kc values are influenced by different climatic conditions and methodologies. Therefore, the purpose of this work was to verify the water mass balance of HFCWs, in order to estimate the evapotranspiration of the system and to determine the appropriate value of Kc for *T. latifolia*.

MATERIALS AND METHODS

Experiment site

The experiment was performed at the School of Agriculture, São Paulo State University (UNESP), Botucatu, SP, Brazil (location: 22°51′9.55″S, 48°25′49.55″W) from November 8, 2015 to April 29, 2016 (total of 25 weeks). The climate in the region is classified as Cfa (Köppen): humid subtropical (mesothermal), with mean temperatures >22 °C in the warmest month (Cunha & Martins 2009).

Treatment system characteristics

The system comprised two HFCWs cultivated with *T. latifolia* (Figure 1). Four rectangular water tanks (100 × 35 × 31 cm) connected in series with a declivity of 1.5% were used for each of the constructed wetlands. Additionally, crushed stones (Ø = 2.4–9.5 mm) with porosity of 51% were used as supporting material. The water tanks were filled with supporting material to the height of 30 cm, and the effluent level was maintained at 25 cm in the final tank in the series. Therefore, each wetland bed had a saturated volume of approximately 160 L, as described by Queluz *et al.* (2017).

Figure 1 | Constructed wetlands of the treatment system.

The HFCWs received a daily single dose of 50 L of secondary domestic wastewater obtained from the wastewater treatment plant of the campus. Therefore, considering the hydraulic loading rate of 3.6 cm d^{-1} and the dimensions of each HFCW, the estimated hydraulic retention time, disregarding effects of evapotranspiration and precipitation, was 3.2 d.

Water mass balance: ETc and Kc calculations

The water balance of the constructed wetlands can be described by Equation (1), suggested by Kadlec & Wallace (2008):

$$\frac{dV}{dt} = Q_i - Q_o + Q_c - Q_b - Q_{gw} + Q_{sm} + (P.A) - (ETc.A) \tag{1}$$

where Q_i is wastewater inflow (L day^{-1}), Q_o is wastewater outflow (L day^{-1}), Q_c is catchment runoff rate (L day^{-1}), Q_b is bank loss rate (L day^{-1}), Q_{gw} is groundwater infiltration (L day^{-1}), Q_{sm} is snowmelt rate (L day^{-1}), P is precipitation (mm day^{-1}), ETc is crop evapotranspiration (mm day^{-1}), A is surface area (m^2), V is volume of stored water (L), and t is time (day). Given local climatic conditions and the characteristics of the HFCWs, some parameters in the equation could be disregarded, which resulted in Equation (2):

$$\frac{dV}{dt} = Q_i - Q_o + (P.A) - (ETc.A) \tag{2}$$

Throughout the experiment, mass loss caused by ETc was lower than mass gained by total inflow (wastewater + precipitation). In addition, the effluent level was controlled and, for these reasons, the maximum volume of water stored in the systems was 160 L. Thus, there was no variation in the volume of stored water in the constructed wetlands; therefore, Equation (2) was set to zero and rearranged as shown in Equation (3):

$$Q_i + (P.A) = Q_o + (ETc.A) \tag{3}$$

As previously stated, the inflow of each HFCW was 50 L day^{-1}. The outflow was measured using water reservoirs that stored the treated effluent from each system, and the collected volume was measured daily by mechanical water flow meters installed in the reservoirs. Daily precipitation data were obtained in the experimental area using an Incoterm wireless digital rain gauge (Model: 4760). The HFCW surface area was determined based on the dimensions of the water tanks (1.4 m^2). Thus, as displayed in Equation (4), daily ETc for the HFCW was calculated by readjusting Equation (3) and using the data mentioned above:

$$ETc = \frac{(Q_i - Q_o + 1.4P)}{1.4} \tag{4}$$

where ETc is crop evapotranspiration (mm day^{-1}), Q_i is inflow (L day^{-1}), Q_o is outflow (L day^{-1}), and P is precipitation (mm day^{-1}).

Daily ETo was calculated using the Penman–Monteith method (Equation (5)), as described in the FAO-56 manual (Allen *et al.* 1998):

$$ETo = \frac{(0.408)\Delta(R_n - G) + \gamma \dfrac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{5}$$

where ETo is the reference evapotranspiration (mm day^{-1}), R_n is net radiation at the crop surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T is mean daily air temperature at 2-m height (°C), u_2 is wind speed at 2-m height (m s^{-1}), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), $e_s - e_a$ is the saturation vapor pressure deficit (kPa), Δ is the slope vapor pressure curve (kPa °C^{-1}), and γ is the psychrometric constant (kPa °C^{-1}). The data described above were collected at the campus by an automatic weather station.

Finally, the value of Kc for *T. latifolia* was calculated using the ratio shown in Equation (6):

$$Kc = \frac{ETc}{ETo} \tag{6}$$

where Kc is the crop coefficient (dimensionless), ETc is crop evapotranspiration (mm day^{-1}), and ETo is the reference evapotranspiration (mm day^{-1}).

RESULTS AND DISCUSSION

Figure 2 shows the precipitation data collected throughout the course of the experiment.

It is evident that rainfall events occurred frequently during the majority of the experimental period. These events altered the inflow of the HFCWs, resulting in variation of the hydraulic retention time. The collected daily precipitation data and the surface area of the constructed wetlands (1.4 m^2) were used to calculate the additional flow caused by the rainfall. For extreme rainfall events, it was considered that the HFCWs could be treated as closed systems, i.e., saturated soil without subsurface flow, and that they could only store a volume of rainwater lower than the available free volume, which is the sum of the unsaturated supporting material pore volume and the freeboard volume of each water tank. Given that the free volumes of the first, second, third, and fourth water tanks were about 23, 19, 15, and 12 L, respectively, the free volume of each constructed wetland was about 71 L. Thus, given the surface area of the constructed wetlands (1.4 m^2) and the available free volume (71 L), this study assumed that rainfall events with precipitation rates >50.7 mm day^{-1} (1.4 m^2 × 50.7 mm day^{-1} = 71 L) inevitably overflowed the water tanks. This impeded the analysis of the data on such dates. For this reason, data

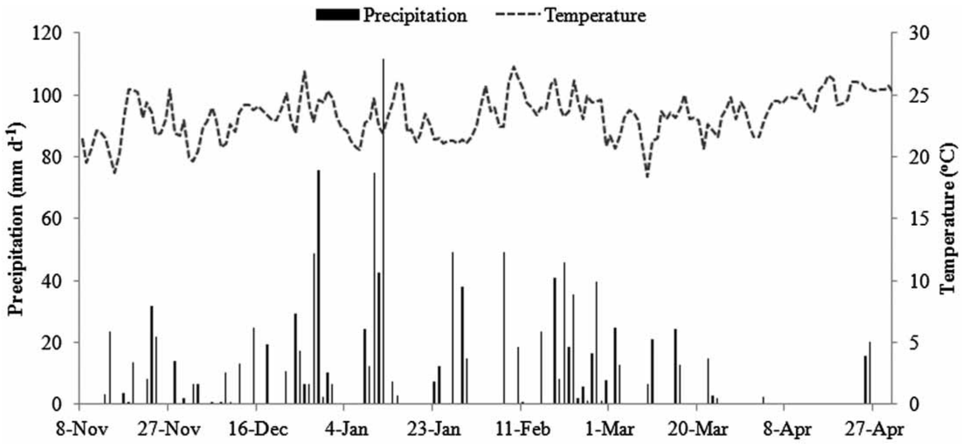

Figure 2 | Precipitation and temperature registered during the course of the experiment.

obtained on the 3 days when the daily precipitation was >50.7 mm were excluded from the analysis of the results. Figure 3 shows the inflow and mean outflow of the HFCWs.

Because of the marked variation of precipitation during the course of the experiment, the daily effluent application rate (50 L day^{-1}) suffered frequent alteration. Precipitation adds water to the system and reduces the hydraulic retention time. Meanwhile, ETc removes water from the system and increases the hydraulic retention time, reducing the outflow. Therefore, the outflow is always lower than or equal to the inflow, as shown in Figure 3. To summarize, the volume of evapotranspirated water in the constructed wetlands is the difference between the inflow and the outflow. In order to calculate the evapotranspirated water layer, the water loss volume and the superficial area of the constructed wetlands were combined using Equation (4). The values calculated for ETc and ETo during the experiment are presented in Figure 4.

The 7-day average ETc results shown in Figure 4 display marked variability ranging from 4.9 to 20.0 mm day^{-1} (daily values range: 0.7–46.6 mm day^{-1}). However, these values are consistent with those found in the literature. This variable is highly affected not only by the macrophyte species used and the latitude but also by the environmental conditions, including solar radiation, humidity, and temperature. Therefore, it is to be expected that research

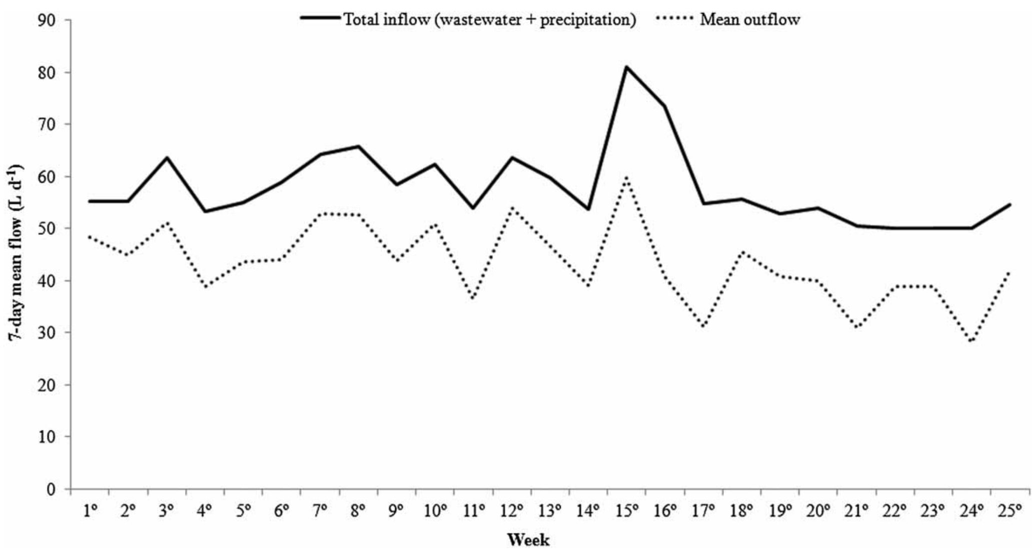

Figure 3 | Total inflow and mean outflow of the two constructed wetlands.

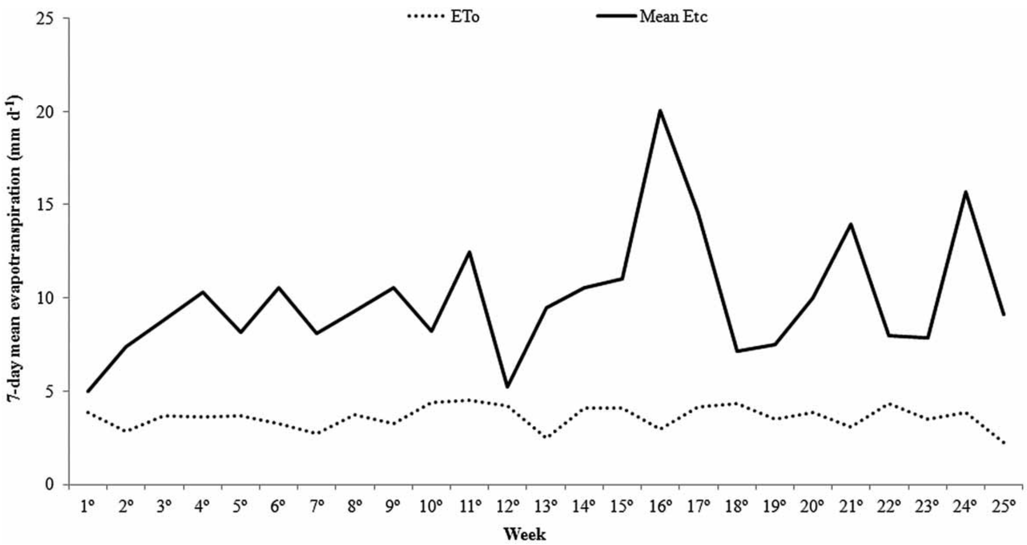

Figure 4 | Crop (ETc) and reference evapotranspiration (ETo) during the course of the experiment.

conducted in other parts of the world exhibits discrepancies in the values for ETc of constructed wetlands. For example, Tuttolomondo *et al.* (2016) obtained ETc values of 1.3–37.0 mm day^{-1} for an HFCW cultivated with *T. latifolia* in Italy. Brasil & Matos (2008) determined mean values for ETc of 4.92–14.03 mm day^{-1} for HFCWs cultivated with *Typha* sp. in Brazil. In addition, Lim *et al.* (2001) calculated values for ETc of 18.2–32.9 mm day^{-1} for subsurface flow constructed wetlands cultivated with *T. angustifolia* in Malaysia. Finally, in Israel, Freedman *et al.* (2014) obtained values for ETc of 19.5–41.8 mm day^{-1} for constructed wetlands cultivated with *B. indica*.

The values of ETc derived for constructed wetlands present considerable variation; therefore, it is reasonable that the maximum value for ETc calculated in the current study was very high, i.e., 46.6 mm day^{-1} (data obtained in the 26th week of the experiment). High values can be associated with base evaporation (Eb), which is promoted by the latent heat of the secondary effluent (Kadlec 2006; Beede *et al.* 2014). The height of the macrophytes and their respective leaf areas are two other factors that might be related to the high values of ETc obtained in this study. Greater heights and leaf areas of the macrophytes lead to greater interception of dry winds. This causes higher ETc in the constructed wetlands (Kadlec & Wallace 2008). Finally, the direct incidence of solar radiation on the sides of the HFCWs may increase the temperature of the mesocosms with a consequent increase in ETc values, as observed in the present study.

Table 1 shows the mean monthly values for ETc and ETo, as well as values for Kc obtained using Equation (6).

The values for ETo displayed in Table 1 are consistent with historical averages recorded by Pereira *et al.* (2016) for the summer period in the same region as where the experiment of the current study was performed. The data in Table 1 show that the mean monthly values for Kc ranged from 2.03 to 3.68 (mean: 2.74). The range of mean values determined for Kc using *Typha* sp. in the literature is wide, ranging from 0.29 to 6.51 (Brasil & Matos 2008;

Table 1 | Mean monthly values for crop evapotranspiration (ETc), reference evapotranspiration (ETo), and crop coefficient (Kc)

	Month						
Parameter	Nov	Dec	Jan	Feb	Mar	Apr	Monthly average
ETc (mm day^{-1})	7.1 ± 3.7	9.2 ± 5.1	9.2 ± 4.6	12.5 ± 11.3	10.5 ± 7.8	10.6 ± 6.2	9.85 ± 1.80
ETo (mm day^{-1})	3.5 ± 1.1	3.4 ± 0.9	4.0 ± 1.1	3.4 ± 1.1	3.7 ± 0.8	3.6 ± 1.0	3.60 ± 0.23
Kc (ETc/ETo)	2.03	2.70	2.30	3.68	2.83	2.94	2.74

Pedescoll *et al.* 2013; Beede *et al.* 2014; Rashed 2014; Tuttolomondo *et al.* 2016). The results obtained by this work show a narrower range for Kc, i.e., 2.03–3.68; nevertheless, the values remain within the range described in the literature.

Brasil & Matos (2008) evaluated ETc and the Kc of HFCWs cultivated with *Typha* sp., obtaining different values for Kc over the course of the experiment. According to the authors, macrophytes can behave similarly to conventional agricultural plants, meaning that the value of Kc depends on the phenological stage of the plants. The Kc values obtained by the authors during the stages of growth, flowering, senescence, and regrowth (after pruning) were 3.00, 4.58, 3.28, and 2.22, respectively. Similar results were also observed by Tuttolomondo *et al.* (2016). Allen *et al.* (1998) suggested the use of different Kc values for every phenological stage of *Typha* sp.: 0.6 during growth, 1.2 during flowering, and 0.6 for senescence. However, for practical reasons, primarily related to the HFCW design process, we recommend the adoption of a fixed value for Kc, e.g., 2.74 (the mean value obtained by this work).

According to Kadlec & Wallace (2008), available information regarding the relation between the surface area and ETc of constructed wetlands is limited. However, these authors affirmed that, typically, the smaller the surface area, the higher the ETc and, consequently, the higher the value of Kc. For example, this work used HFCWs with surface areas of 1.4 m^2 cultivated with *T. latifolia*, giving a calculated mean value for Kc of 2.74. Similar results were also obtained by Beede *et al.* (2014), who evaluated an HFCW with a surface area of 2.0 m^2 cultivated with *T. latifolia*, obtaining a value for Kc of 2.5. On the other hand, Abtew & Obeysekera (1995) measured the Kc of a wetland system comprising 549 hectares cultivated with *T. latifolia* and they obtained a value of 1.0. These results demonstrate there is a relation between the size and ETc of constructed wetland systems. It is worth mentioning that, presumably due to the much higher edge/area ratio, this phenomenon is considered to occur because of the 'Oasis Effect' (Kadlec & Wallace 2008; Beede *et al.* 2014). Hence, the results obtained in the present study are not representative of a system at field scale.

A few limitations of the present study must be recognized: 1) the structural form of the HFCWs allows the incidence of solar radiation in the sides of the mesocosms with consequent increase of ETc; 2) the outflow measurement was performed by a simple and low-cost method (water reservoirs + mechanical water flow meters) that may be less accurate than more refined methods, i.e., digital volumetric flow meter, however the adoption of similar and simple methods are reported in the literature (Headley *et al.* 2012; Pedescoll *et al.* 2013).

CONCLUSIONS

Despite the limitations, the results from this work show that a subsurface flow constructed wetland is a dynamic system, and that its hydraulic behavior is influenced directly by precipitation and evapotranspiration. In addition, the results demonstrate the importance of ETc for the HFCW water mass balance, because it reduces the outflow considerably, which in turn is responsible for increasing the total concentration of pollutants. These findings indicate that water loss caused by evapotranspiration should be considered when designing constructed wetlands. The wide range of variation in ETc for HFCWs should be noted, with maximum values higher than observed for conventional agricultural crops. The value of Kc for *T. latifolia* depends on the phenological stage; unsurprisingly, the literature reports a wide range of values. Therefore, it would be preferable to adopt a fixed value for Kc in the design process of HFCWs, e.g., 2.74, which is the value obtained in this work. This study is relevant, because the findings offer a direct link between theoretical research of biological and hydrological parameters and their application in wastewater treatment and engineering.

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