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Optimization of the wastewater treatment capacity of a short rotation willow coppice vegetation filter

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Abstract

The objective of this study was to determine the conditions to optimize the wastewater treatment efficiency of a short rotation willow coppice (SRWC) plantation (*Salix miyabeana* 'SX67') used as a vegetation filter to treat small municipal primary effluents (with less than 800 population equivalent). With the aim of maximizing the annual amount of wastewater treated, the effect of adjusting the hydraulic loading rate (HLR) according to the estimated evapotranspiration was tested at demonstration scale under humid continental climate conditions. We proposed a new method to calculate the evapotranspiration rate from plant physiological data, introducing an α factor based on direct transpiration measurements. This method increased the accuracy of the water balance, with a prediction of the crop coefficient (k_c) based on either an seasonal approach (R^2 of 0.88) or a monthly approach (R^2 of 0.94). This led to a more precise estimation of the pollutant loading reaching the groundwater and could be used after plantation establishment as a fine-tuning tool. Adjusting the HLR to that of evapotranspiration between May and October led to an annual increase of 2 mm/d (around 0.35 m^3/m^2 per growing season) in HLR, while maintaining a pollutant loading removal efficiency of at least 96% for organic matter, 99% for total phosphorus and 93% for total nitrogen. A high HLR at the end of the season

caused nitrogen leaching into groundwater, indicating that the HLR should be decreased in October, when willow growth is greatly reduced.

Keywords:

wastewater treatment, municipal wastewater, evapotranspiration, willow, short rotation coppice, vegetation filter

List of symbols and abbreviations

A	Net photosynthesis
BOD_5	Biochemical oxygen demand (5 days)
C	Control plot
COD	Chemical oxygen demand
DP	Deep percolation
ET	Evapotranspiration
ET_c	Crop evapotranspiration
$ET_{c,adj}$	Adjusted crop evapotranspiration
ET_{exp}	Evapotranspiration estimated from data
ET_{lit}	Evapotranspiration from literature
FM	Flowmeter
G_s	Stomatal conductance
HLR	Hydraulic loading rate
HRT	Hydraulic retention time
Inf	Influent
IRGA	Infrared gas exchange analyser
Irr	Irrigation
k_c	Crop coefficient used to estimate crop evapotranspiration
LAI	Leaf area index
L0	Loading 0 – Potable underground water
L1	Loading 1 – Primary municipal wastewater
L2	Loading 2 – Primary municipal wastewater

NH_4	Ammonia (free and saline)
NO_x	Nitrite and nitrate
p	Atmospheric pressure
RAW	Readily available water
SRWC	Short rotation willow coppice
St	Value from the study referred to for comparison (subscript)
T	Willow transpiration
TKN	Total Kjeldahl nitrogen
TN	Total nitrogen
TAW	Total available water
TP	Total phosphorus
Tr	Treatment for which the correction is applied (subscript)
TSS	Total suspended solids
U	Underground tap water
VPD	Vapor pressure deficit
W	Primary effluent (wastewater)
WRRF	Water resource recovery facility
WUE	Water use efficiency
Z_r	Rooting depth

1. Introduction

Short rotation willow coppice (SRWC) used as a vegetation filter represents a wastewater treatment process that could be used by small municipalities (e.g. 300 to 800 population equivalent) (Dimitriou and Aronsson 2011, Guidi Nissim et al. 2015, Hasselgren 1998, Lachapelle-T. et al. 2019). The efficiency of such treatment depends on critical parameters such as soil conditions, plant physiological characteristics and wastewater hydraulic loading rate (HLR).

Soil texture and composition affect how water percolates and becomes available to plants. Clay-based soils retain more water than sandy soils but being denser, they reduce plant growth by restricting root penetration and elongation (Lafleur et al. 2016). With their typically high level of organic matter and nutrient content, clay-based soils improve soil fertility (Havlin et al. 2013). Sandy soils, however, have a higher hydraulic conductivity, which improves water infiltration and aeration, favoring organic matter decomposition, but do not retain water and nutrients as well as clay-based soils (Van Veen and Kuikman 1990).

The selection of plants for use in wastewater treatment by short rotation coppice vegetation filter depends on the desired goal, which can be to maximize (e.g. zero-discharge wetland) or minimize the evapotranspiration (ET) rate (in an arid climate) (Headley et al. 2012). Fast-growing willow shrubs can be a good choice for humid climate where precipitations are well distributed throughout the growing season and for which maximizing ET is desirable to minimize water discharge (Guidi Nissim et al. 2015, Jørgensen and Schelde 2001). Cultivars of *Salix miyabeana* have been studied extensively and have exhibited good performance for environmental purposes in various projects in Eastern Canada (Guidi Nissim et al. 2015, Guidi Nissim et al. 2013, Guidi Nissim et al. 2014, Jerbi et al. 2014, Lachapelle-T. et al. 2019, Mirck and Volk 2010).

The ET rate affects wastewater treatment efficiency. A high ET rate leads to a reduction in the mass of contaminants discharged but, in some cases, may result in an increase in the pollutant concentration in the water treated due to the reduction of dilution water (Zhao et al. 2012). Setting aside runoff and capillary layer rise, the deep percolation (DP) can be calculated from the water balance, including irrigation (Irr) and rain, according to equation 1 (Allen et al. 1998):

$$DP = (Irr. + Rain)_{IN} - ET \quad (1)$$

The ET rate is often estimated by the Penman-Monteith equation combined with crop coefficients (k_c) measured for a given species watered as needed (Allen et al. 1998). The k_c curve provides the seasonal tendency of the plant ET rate, but it is recommended that local data be collected to consider specific cultural practices and regional pedoclimatic conditions (Pereira et al. 2015). Without specific on-site data, the uncertainty in water balance becomes high, increasing the risks of discharging high loads of pollutants to the groundwater. Thus, there is a need to develop a method to adapt the crop coefficient derived from the literature to on-site conditions.

To optimize wastewater treatment efficiency of a vegetation filter, the HLR is more important to consider than plant selection or soil type (Jonsson et al. 2004). A high HLR favors a higher rate of pollutant loading removal but may result in increased deep percolation (or runoff). A low HLR leads to an improved groundwater infiltration water quality, but a lower treatment capacity (Jonsson et al. 2004).

When the HLR is kept constant over the growing season, it will often result in an imbalance between the needs of plants for water nutrients and their availability throughout the growing season (Lachapelle-T. et al. 2019). The HLR can be adjusted according to ET and meteorological conditions according to daily, seasonal and annual variations. Increasing the HLR may change soil water saturation and aeration, and its effects on groundwater water quality is not well understood. Changes in soil conditions can affect biological treatment (Havlin et al. 2013). Soil moisture sensors can be used to monitor the amount of water needed to maintain adequate conditions and modulate the influent flow rate (Cardenas-Lailhacar and Dukes 2010, Romano 2014).

Willow biomass yield (which is related to ET) varies depending on the number of years of plant growth and coppicing (Volk et al. 2011). Variations make the design more difficult to implement reliably, when it is not possible to measure ET extensively. A better knowledge of the expected ET, however, would improve the design reliability and predictability. The originality of this work is to suggest a new approach to help fine-tune the irrigation HLR over the years with in-field ET measurements.

The objective of this study was to determine the conditions optimizing the wastewater treatment capacity of an SRWC vegetation filter to treat municipal primary effluent wastewater. It also aimed to develop a method to adjust the crop coefficient from plant physiological data and to determine the consequences on the quantity and quality of the deep percolation water. Four HLRs were tested during a two-year demonstration scale project. The water balance and the water treatment efficiency were characterised for every loading rate over the two growing seasons to optimise the SRWC vegetation filter treatment efficiency.

2. Materials and methods

2.1. Experimental site

The SRWC vegetation filter was installed in a two-hectare willow plantation (*Salix miyabeana* 'SX67' at 16 000 plants/ha) established in 2008 and harvested in 2011 and 2015 (two-year-old stems on ten-year-old plants in the fall of 2017). The experimental site is located near the local water resource recovery facility (WRRF) of St-Roch-de-l'Achigan, Québec, Canada (45˚51'29" N, 73˚35'36" W, 52 m above sea level). From 2008 to 2012, an experiment was conducted with a secondary municipal effluent on the same plantation. (Guidi Nissim et al. 2015, Jerbi et al. 2014).

The climate of the region is humid continental with marked seasonal temperature variations. The nearest weather station is located 15 km away at l'Assomption, Québec (45˚48'34''N, 73˚26'05''O) and, for the period from 2003 to 2017, it recorded an annual average minimum and maximum temperature of 1 ± 12 ˚C and 11 ± 13 ˚C, respectively. On site measurements were recorded during the study, between May 1 and October 31, 2017. the on-site weather station measured average minimum and maximum temperatures during this period of 9.8 ± 5.6 ˚C and 22.1 ± 6.5 ˚C, respectively, close to the 10.3 ± 5.7 ˚C and 21.6 ± 6.4 ˚C values for the 2006 to 2016 period recorded by Environment Canada (2018). The local WRRF measured total rainfall during the growing season of 680 mm, which was higher than the mean of 602 mm observed for the last 10 years by Environment Canada (2018) (Fig. 1). An on-site weather station (*Vantage Pro2, Davis Instruments*) recorded minimum and maximum temperature, relative humidity, solar radiation and wind speed at a 30-minute interval.

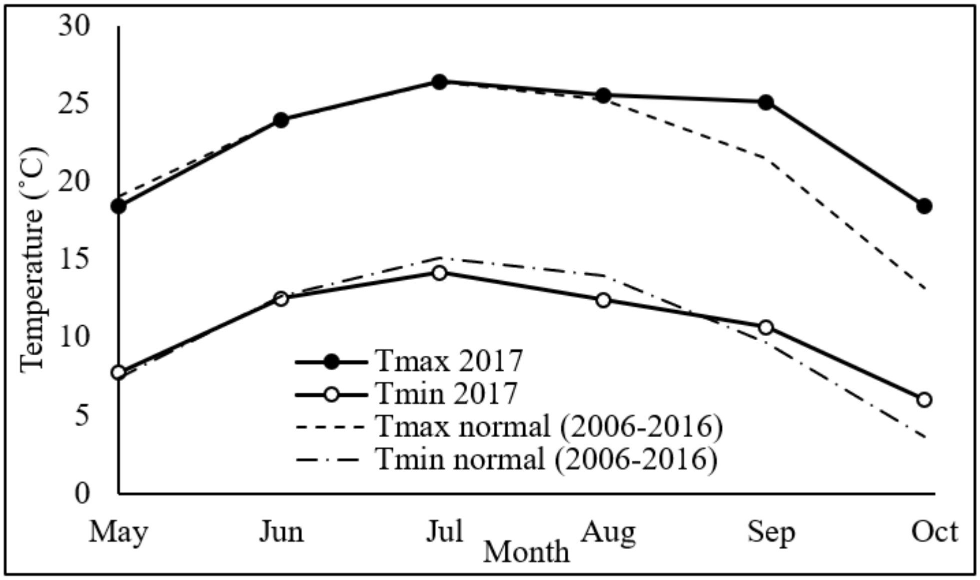

Fig. 1 Monthly minimum and maximum temperatures recorded on-site for 2017 compared to normal temperatures (2006-2016) from the nearest weather station (Environment Canada 2018)

Soil characterization showed that the first layer of soil (0-30 cm) was a silty sand, (79% sand, 17% silt and 4% clay), followed by sand (sand 88% with 8% silt and 4% clay; 30-70 cm) and clay (> 70 cm). There was little total available soil water in the top layer (8%) that displayed a high saturated hydraulic conductivity (2.0 to 14.0 E−03 cm/s). More detailed information about soil conditions was published previously (Lachapelle-T. et al. 2019).

2.2. Experimental design

The current experiment is a follow-up study conducted during the summer of 2016 (July 20 to November 8, 111 d) with results published by Lachapelle-T. et al. (2019). The HLR for 2016 was kept constant over the season. Results of the study were positive but highlighted the need to better distribute the irrigation during the growing season, to avoid imbalances between irrigation and willows need.

For 2017 (May 29 to November 8, 163 d), the HLR was increased from July 4 to September 28 to account for the increase in willow ET. After September 28, the HLR was decreased back to the pre-July 4 value.

Four irrigation loadings (treatments) were applied with three replicates each, for a total of twelve experimental plots, each measuring 108 m^2(10 m x 10,8 m). The position of each plot was determined to prevent cross contamination via groundwater. Three control plots (C) with no irrigation were included in the study. Plots of the loading 0 (L0) were irrigated with potable underground water, while plots of loading 1 (L1) and loading 2 (L2) were irrigated with a primary wastewater effluent. The 2016 base irrigation loadings were applied at the start and at the end of the 2017 season (May 29 to July 4 and September 28 to November 8; L0 and L1: 10 mm/d and L2: 15 mm/d). Each loading was increased by 50% during the seasonal ET peak (July 4 to September 28; L0 and L1: 15 mm/d and L2: 24 mm/d). For L0, a paddle-wheel flowmeter installed upstream from each plot measured the volumes applied. For L1 and L2, a magnetic flowmeter controlled the volume of primary effluent pumped to the SRWC. Irrigation occurred during the day to maximize ET and the irrigation sequence was changed every two weeks, to change time of day of the irrigation for every plot.

Four rows out of six were irrigated for every plot (72 m^2 irrigated out of 108 m^2 total). Three soil pore water sampling points were set up in each irrigated plot in three different rows, near the irrigation points, for a total of 27 sampling points. Each soil pore water sampling point consisted of a suction cup lysimeter (Soilmoisture Equipment Corp. 1900L near-surface samplers, USA) installed at a depth of 60 cm, according to the manufacturer's instructions (Soilmoisture Equipment Corp. 2007).

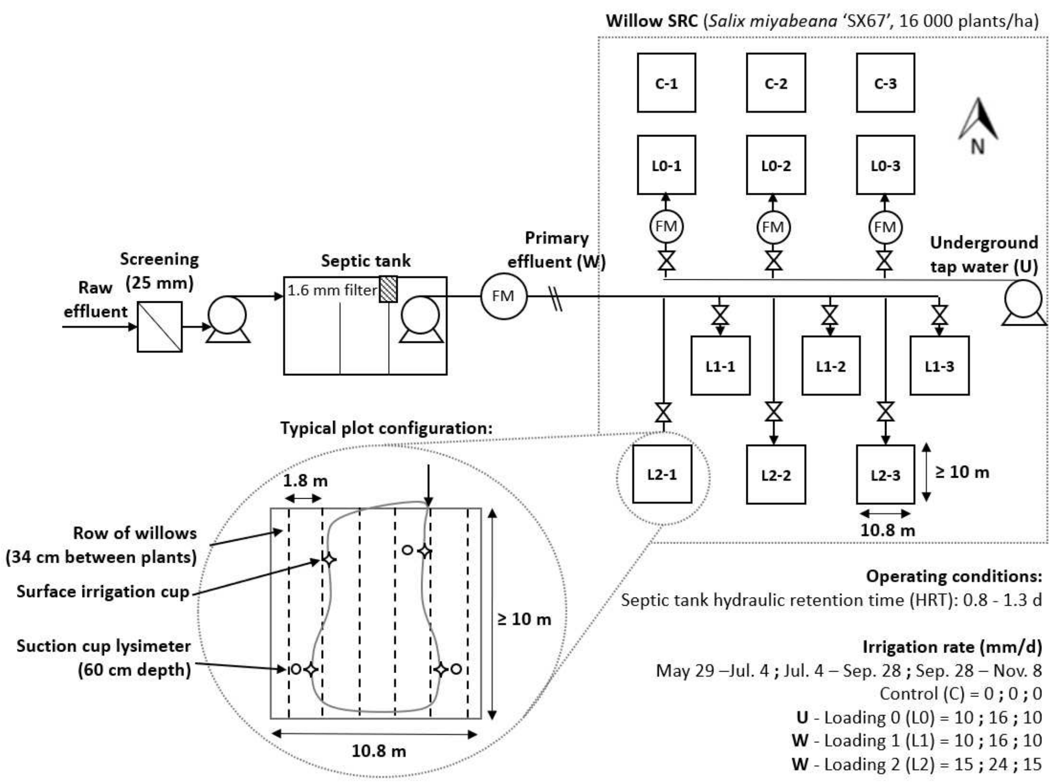

Fig. 2 Experimental setup schematic. Adapted from Lachapelle-T. et al. (2019). Note: FM = flowmeter.

2.3. Stomatal conductance and photosynthesis measurements

During 2017, on three occasions (August 7 and 21 and September 21 between 10 am to 2 pm), the net photosynthesis 'A' (CO_2 assimilation rate in μmol CO_2 m^{-2} s^{-1}) and the stomatal conductance 'G_s' (water vapor in mmol H_2O m^{-2} s^{-1}) were measured with a portable infrared gas exchange analyser (IRGA), according to the manufacturer's instructions (LI-COR 6400 XTR Biosciences, USA). During measurement, the airflow was set to 500 μmol/s and leaf temperature was maintained at 26 ± 0.5 °C.

Four trees per plot and a single leaf per tree were tested for each loading studied (48 measurements per day, including control plots). Each measurement was taken on a fully expanded healthy leaf, located at two thirds of the plant height, on a clear windless sunny day. Prior to gas exchange measurements, the intrinsic water use efficiency (WUE) was calculated with the ratio of A and G_s, as presented in equation 2:

$$WUE_{Intrinsic} = A/G_s \ (\mu\text{mol } CO_2/\text{mmol } H_2O) \quad (2)$$

The WUE being an ecophysiological attribute, it should remain nearly constant for plants of the same species or cultivars (Bacon 2004).

2.4. Evapotranspiration modeling

Considering the high plantation density (16 000/ha) and the large leaf area of *S. miyabeana* 'SX67' (Tharakan et al. 2005), ET is mainly due to leaf surface

(Shuttleworth and Wallace 2007), and we assumed that it can be estimated based on tree transpiration (Frédette et al. 2019). We assumed that this simplification was applicable to an SRWC, especially with the fertilized plots where the leaf cover is dense. Tree transpiration was estimated according to equation 3.

$$ET_{SX67} = G_s * LAI_{active} * \frac{VPD}{p} \quad (3)$$

Stomatal conductance (G_s; μmol H_2O m^{-2} s^{-1}) can be converted into mm (m^{-2} leaf d^{-1}) using the molar volume of H_2O and the mean monthly mean of hours of bright sunshine per day. Combined with the leaf area index (LAI_{active}; leaf m^2/soil m^2) and the ratio of the vapor pressure deficit to the sea level barometric pressure (VPD/p), it can be used to estimate transpiration.

G_s and VPD were measured three times during the summer. These measurements did not provide sufficient information about the transpiration that occurred over the whole growing season, but it was used to assist in validating our results.

Since crop ET calculations need precise crop coefficients, which can be hard to estimate, we proposed an α factor based on the ratio between transpiration measured during this study and that obtained from more extensive studies where crop coefficients had been measured with the same tree genus. The method aims to adjust crop coefficient measured in another study to local on-site condition (like soil texture and nutrients availability). The proposed α method is presented in equations 4 and 5.

$$ET_c = (\alpha * k_c) * ET_0 \quad (4)$$

where,

$$\alpha = \frac{Transpiration_{tr}}{Transpiration_{st}} = \frac{\left(Gs_{tr} * LAI_{tr} * \frac{VPD_{tr}}{p}\right)}{\left(Gs_{st} * LAI_{st} * \frac{VPD_{st}}{p}\right)} \quad (5)$$

- ET_c: crop evapotranspiration (mm/d)
- ET_0: reference evapotranspiration calculated with Penman-Monteith equation (mm/d)
- k_c: crop coefficient (unitless)
- α: correction coefficient with field data (unitless)
- Gs: stomatal conductance (mm H_2O m^{-2} d^{-1})
- LAI: leaf Area Index (m^2 leaf/m^2 soil)
- tr: (subscript) treatment for which the correction is applied
- st: (subscript) value from the study compared to. In this study, compare to Frédette et al. (2019)

The ET was calculated with the Penman-Monteith equation, using the FAO 56 report method for daily calculation (Allen et al. 1998). Crop evapotranspiration (ET_c) for L1 and L2 (fertilized zone) was estimated with the corresponding crop coefficient (second year of growth) measured for *S. miyabeana* 'SX67' in a constructed wetland under the same climate and genus (Frédette et al. 2019). To account for the unfertilized effect, ET_c for L0 was estimated from a correction between fertilized and unfertilized crop coefficient (Guidi Nissim et al. 2008), but with the k_c curve tendency measured in the same climate (Frédette et al. 2019). Mean reference evapotranspiration (ET_0) calculated was 2.9 mm/d, for a total of 530 mm for the growing season.

Since LAI was not directly measured in this study, we assumed that it was identical to that determined by Frédette et al. (2019) considering the visually similar high-density of the plantation and canopy of both plantations. The absence of LAI measurements made it impossible to apply the method to unfertilized plots for which the LAI was smaller than the fertilized plot. To improve the precision of the ratio, the transpiration rate was calculated daily (ex: August 7 G_s with the daily LAI and VPD) and the mean value was used in the calculations. Since the field measurements were made in August and September, it was assumed that this period was representative of the whole season. The ratio was calculated with the mean for the same period (August and September) but applied to the whole k_c curve.

The proposed method was calibrated using the data published by Frédette et al. (2019). While applying the α method to compare the first and second year (2016 and 2017), we expected to generate the same crop coefficients obtained by the whole model proposed by Frédette et al. (2019). Since the LAI curves have the same tendency and to simplify the model, only the LAI max (11.6 for 2016 and 13.3 m^2/m^2 for 2017) was used for each year instead of the monthly variation (Frédette et al. 2019). Two applications of the method were tested; with the ratio applied on either the monthly mean (monthly approach) or the yearly mean (seasonal approach).

2.5. Water balance

A small 200 mm dike was used to protect every plot from runoff, so that only irrigation and the rain that fell directly on the plot entered the system. The capillary rise was assumed to be zero, considering the daily calculation (Allen et al. 1998). The only outputs were ET and DP. Root zone water availability (RAW) was assessed daily considering that the rooting depth (Z_r) was at 0.3 m (Jerbi et al. 2014) and that the total available water (TAW) was 24.6 mm calculated from the root zone depth (Saxton and Rawls, 2006). The ET was adjusted ($ET_{c,adj}$) to take into account plant stress due to a lack of available water in the soil (Allen et al. 1998). DP was calculated daily from a water balance between the rain, the irrigated water, the evapotranspiration and the root zone depletion at the start of the day (D_r).

2.6. Wastewater treatment characterization

Wastewater treatment efficiency was determined every two weeks (8 times in 2016 and 12 times in 2017). An automatic refrigerated sampler took 24-hour composite samples at 42 mL/h (total of 1 L) from the primary effluent. A lysimeter in each plot collected soil pore water over the day according to the manufacturer's instructions (Soilmoisture Equipment Corp 2007) to characterize the DP. The pore filtration size of the lysimeter was 1.4 μm.

A flow injection analysis system (Quickchem 8500, Lachat Instruments) was used to determine total phosphorus (TP), total Kjeldahl nitrogen (TKN), nitrate plus nitrite (NOx) and total ammonia (NH_4) by colorimetry (APHA et al. 2017). TKN and NOx concentration were summed up to calculate the total nitrogen (TN) concentration. The chemical oxygen demand (COD) was determined by the Hach colorimetric method (Hach method 8000, APHA et al. 2017). Typical municipal wastewater COD to BOD_5 ratios were used to estimate the primary effluent BOD_5 (EnviroSim Associates Ltd 2015). The NOx and NH_4 were determined on filtered influent samples (0.45 μm) to characterize soluble components.

The mean influent characteristics in 2017 were 290 mg/L of chemical oxygen demand (COD), 42 mg N/L and 20 mg N/L for total nitrogen (TN) and NH_4, respectively. The mean total phosphorus (TP) was 4.1 mg P/L, the pH 7.6 and the total suspended solids (TSS) 56 mg /L.

2.7. Removal efficiency

Contaminant loadings were calculated for the influent and the DP for two-week periods, assuming that the sample was representative of the period. The influent loading (g m^{-2} d^{-1}) was calculated by combining the influent concentration (mg/L) and the volume of wastewater pumped over the two-week periods (L). The DP loading (g m^{-2} d^{-1}) was estimated from the soil pore water concentration (collected from the lysimeter) (mg/L) and the volume of DP water estimated for the same period (L).

2.8. Statistical analysis

One-way analysis of variance (ANOVA) with a significance level of 5% were conducted on A, Gs and WUE to determine if the loadings applied had a significant effect on the parameters. A post-hoc Tukey honestly significant difference (HSD) verified the impact of the treatment on the parameters. The statistical model consisted of four treatments (control, L0, L1 and L2) and three blocks as random factor (three replicates for each loading). Normality of the residuals was assessed visually visually with quantile-quantile plots, and log transformed for G_s. All tests were conducted using JMP 14 (SAS Institute, Cary, NC).

Linear regression between the crop coefficients generated by the application of the α method and the crop coefficients from Frédette et al. (2019) was used to evaluate the validity of the method. A high R^2 indicated that the results obtained by the α method were similar to the original one.

3. Results

3.1. Calibration of the α factor

The α method calibration results based on data from Frédette et al. (2019) are presented in Table 1. The maximum transpiration for 2016 and 2017 occurred in July (35 and 24 mm/d) and August (33 and 23 mm/d). The monthly α factors calculated for years 2016 and 2017 were between 1.12 (September) and 1.51 (May). The seasonal mean value for the α factor for the seasonal approach was 1.34. The monthly difference between the α method and the model from Frédette et al. (2019) was less than 10% from May to September, which represented 97% of the growing season ET. Using the seasonal α factor, the error was less than 11% for May to August, which represented 86% of the total estimated ET. The monthly α method predictions were closer ($R^2 = 0.94$) than the seasonal method ($R^2 = 0.88$; Fig. 3). The percentage of the seasonal ET estimated for this study is also shown as a reference to determine the effect of the error on the total estimation of the seasonal ET. Most ET (76%) took place between June and August.

Table 1 Calibration results (k_c 2016 generated from the proposed α method applied over 2017 k_c). T = transpiration, ET = evapotranspiration.

Month	T 2016	T 2017	$\alpha_{16/17}$	Monthly difference	Seasonal difference	Monthly % of seasonal ET
Units	mm/d	mm/d	-	%	%	%
May	20	13	1.51	1	11	10
June	24	19	1.25	10	4	22
July	35	24	1.45	-5	3	30
August	33	23	1.46	-6	2	24
September	17	15	1.12	-3	-23	11
October	8	6	1.28	-53	-62	2
Mean/ total	23	17	1.34	-5	-5	99

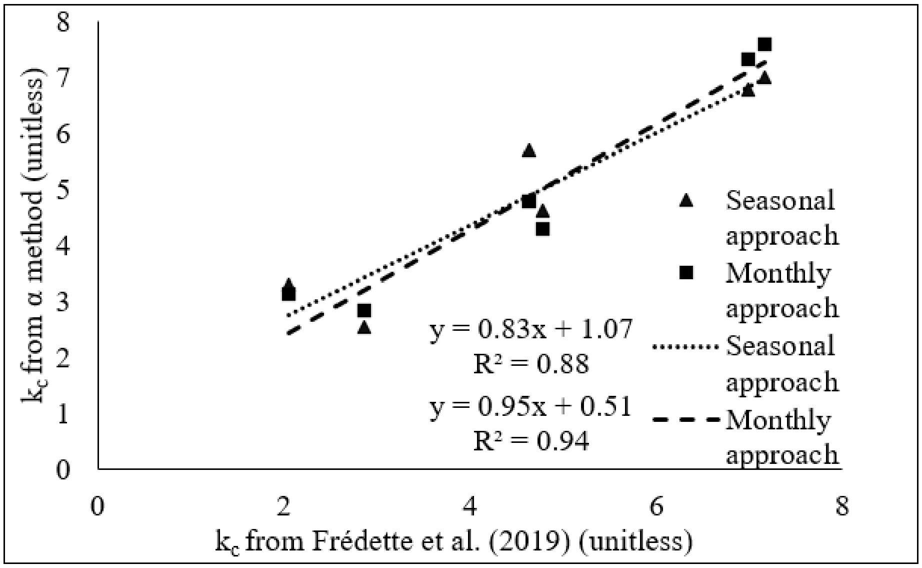

Fig. 3 α method calibration result comparing the k_c generated from the method with the k_c from Frédette et al. (2019)

3.2. α method application

The results of the α method application to compare the data from this study and those from Frédette et al. (2019) are presented in Table 2. The stomatal conductance increased significantly with the loadings applied, from 310 ± 100 mmol H_2O m^{-2} s^{-1} (control) to 520 ± 120 mmol H_2O m^{-2} s^{-1} (L2; Table 2). The same trend was observable for photosynthesis, with 14.2 ± 2.4 (control) to 22.8 ± 2.9 (L2). The $WUE_{intrinsic}$ were between 0.046 μmol/mmol (L2) and 0.051 μmol/mmol (control).

The α factors were calculated from transpiration data obtained in this study (T_{tr}) and the August and September mean transpiration values derived from Frédette et al. (2019) (T_{St2016}=25.1 mm/d and T_{St2017}=18.9 mm/d). Only the August and September data from the latter source were used to calculate the α factors since the data in this study were limited to that two-month period.

The α factors were calculated for the two reference years and the results are presented in Table 2. Most of the α factors were lower than 1.00. The k_c generated from α_1 and α_2 had a low standard deviation (4-5%) for a high k_c value (June to August) (Fig. 4). The May difference was higher (12%), but September and October had larger standard deviations (22 and 59%). The values generated from 2016 were chosen for this paper, considering that they estimated lower values of kc for these periods.

Table 2 Stomatal conductance (Gs), photosynthesis (A), intrinsic water use efficiency ($WUE_{intrinsic}$), transpiration (T) and α factor for each treatment studied compared to the two years of Frédette et al. (2019) (α_{2016} used T_{St2016} = 25.1 mm/d and α_{2017} used T_{St2017} = 18.9 mm/d). Notes: tr: (subscript) treatment for which the correction is applied and st: (subscript) value from the study compared to (Frédette et al., 2019 in this case).

Treatment	Gs	A	$WUE_{intrinsic}$	T_{tr}	α_{2016} (T_{tr} / T_{St2016})	α_{2017} (T_{tr} / T_{St2017})
Units	mmol H_2O m^{-2} s^{-1}	μmol CO_2 m^{-2} s^{-1}	μmol/mmol	mm/d	-	-
Control	310 ± 100^{c}	14.2 ± 2.4^{c}	0.051 ± 0.017^{a}	11.9	0.48	0.63
L0	320 ± 70^{bc}	15.0 ± 2.4^{b}	0.049 ± 0.010^{a}	12.6	0.50	0.66
L1	440 ± 140^{b}	19.4 ± 2.9^{a}	0.048 ± 0.015^{a}	17.3	0.69	0.91
L2	520 ± 120^{a}	22.8 ± 2.9^{a}	0.046 ± 0.011^{a}	20.7	0.83	1.09

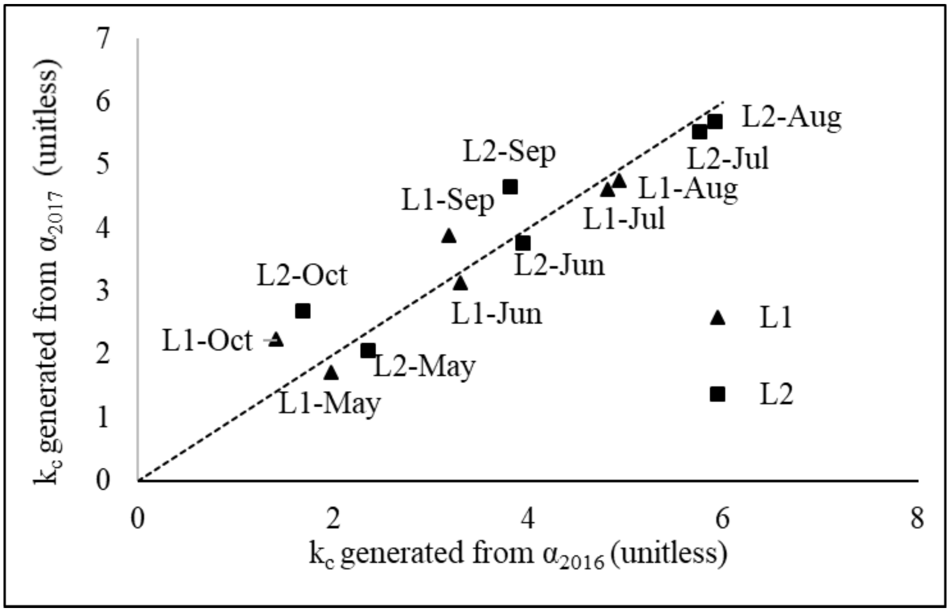

Fig. 4 Correlation between k_c values determined for the wastewater loading rates L1 and L2 generated from α_{2016} and α_{2017} (see Table 2)

3.3. Water balance

The water balance results calculated on a two-week basis are shown in Fig. 5. The ET increased along with the HLR, which resulted in lower levels of DP. The DP pattern followed that of rain for L1. At the end of September, while the ET dropped, there was a high DP period (40% of total DP for 17% of total irrigation) which indicated that the HLR exceeded the system treatment capacity at the end of the growing season. The L2 water balance followed the same general pattern as L1. The main difference was that the HLR was higher than the ET rate, which caused higher levels of DP.

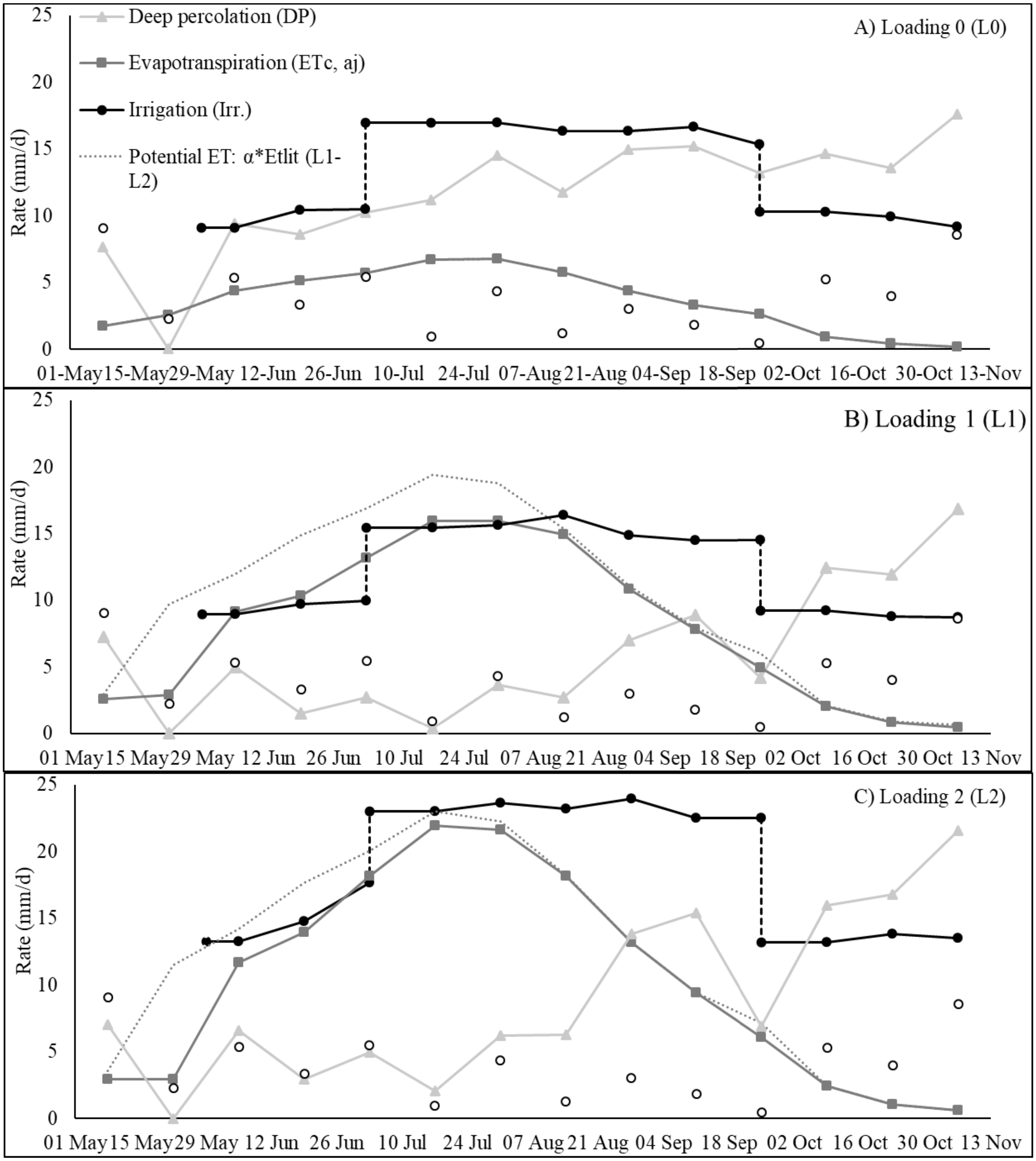

Fig. 5 Estimated water balance for 2017 A) loading 0 B) loading 1 C) loading 2 (the evapotranspiration was corrected with the α factor).

3.4. Treatment efficiency

The total nitrogen (TN) concentration (mg N/L) results for 2016, from Lachapelle-T. et al. (2019), and 2017 (this study) are presented in Fig. 6. The ET curves for both years are presented as a reference. The DP water concentrations were under 6 mg N/L, between May to September for both years, while the plant needs and estimated ET were high (Fig. 6). The TN concentration in the DP water showed the same pattern in 2016 and 2017 with a low concentration until mid-September, then a peak until mid-October and a decrease at the end of October. The ET dropped at the same point that the TN increased, in mid-September.

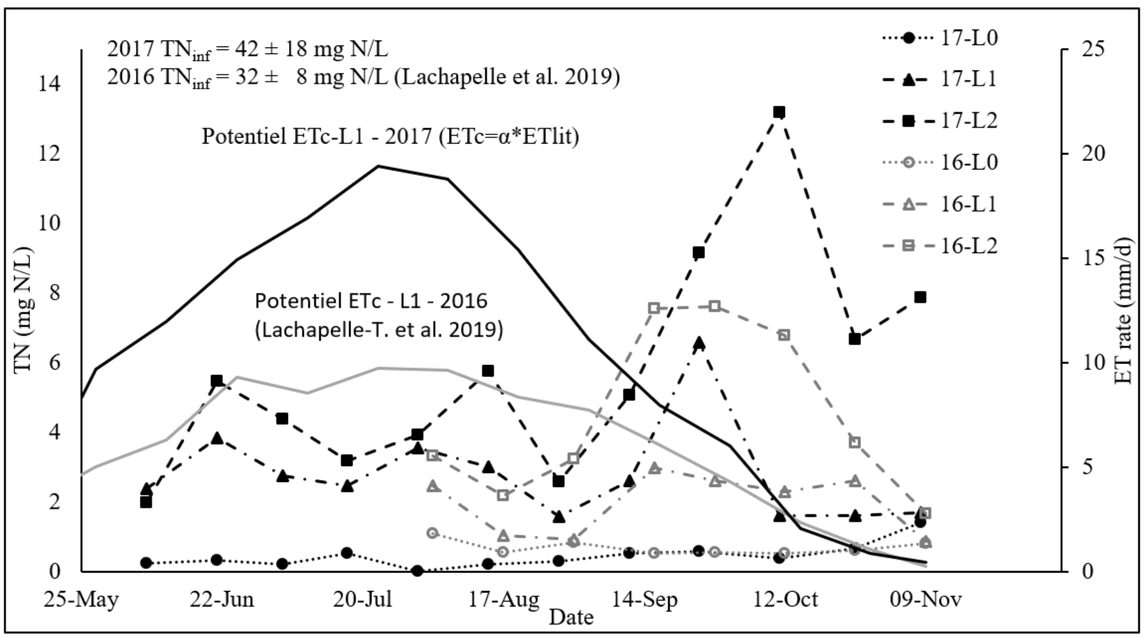

Fig. 6 Comparison of total nitrogen (TN) concentration means and evapotranspiration after treatment (60 cm, sample with lysimeter; with symbols and lines) for seasons 2016 (Lachapelle-T. et al. 2019) and 2017. Note: 17-L0 represents loading 0 for growing season 2017 and ETc stand for crop evapotranspiration.

TN and TKN loading removal efficiencies over the growing season were similar for L1 and L2 (Fig. 7). TKN loading removal decreased slightly at the beginning of November from 98 to 91% but remained constant over the course of the growing season. TN removal remained near 90% until the end of September and then decreased to 45% by November 9. The TN curve followed a similar tendency as the ET curves, and they all reached their highest and lowest points at the same time. This can be explained by the effect of ET on the DP (quantity) and the higher concentration in the DP water at the end of the growing season (quality). Nonetheless, while the irrigation was at its peak in July, the loading removal was still greater than 90%. The drop of loading removal was approximately similar between TKN and TN for L1.

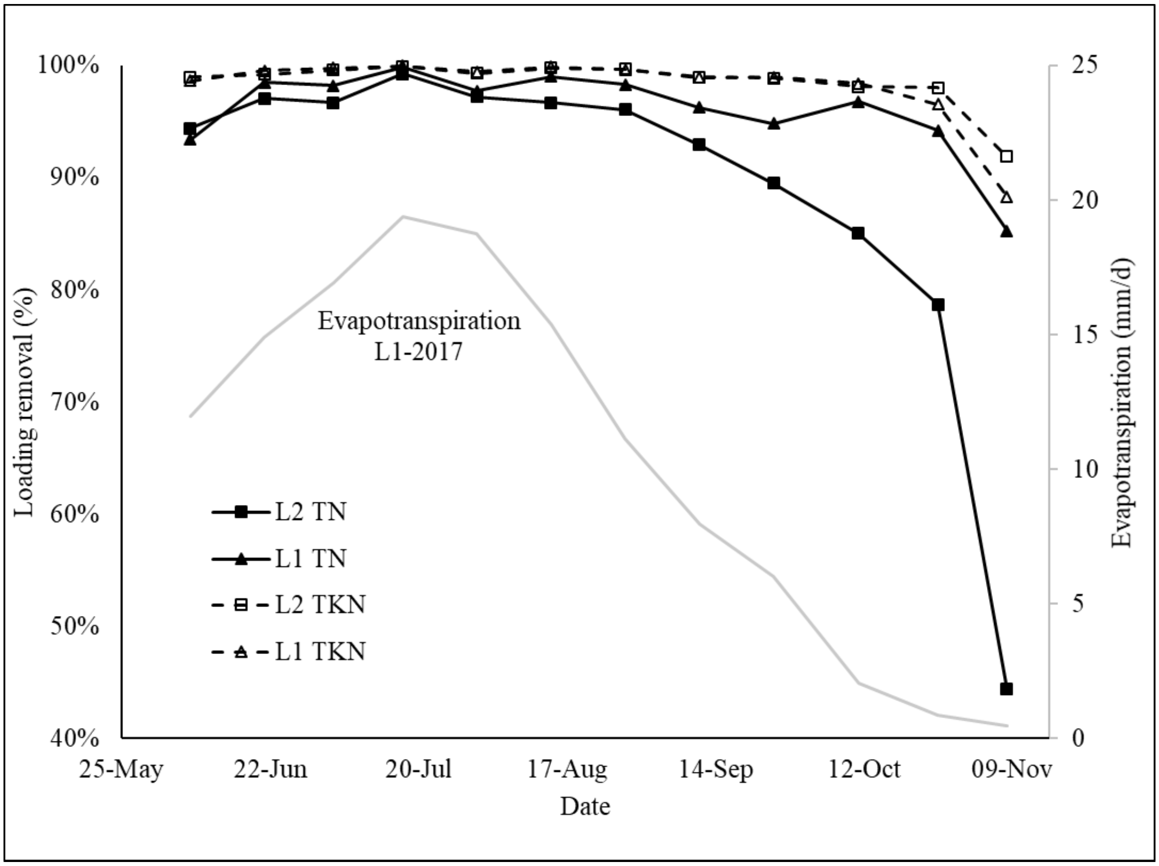

Fig. 7 Total nitrogen (TN) and total Kjeldahl nitrogen (TKN) loading removal for the 2017 season

Chemical oxygen demand (COD), TP and TN treatment efficiencies for 2017 are shown in Table 3. The mean concentration of COD in the DP water and the annual loading removal for the organic matter was similar for L1 and L2 (20 mg/L and 96%, respectively). The TN concentration was higher and the loading removal lower for L2, which indicated that TN treatment efficiency was limiting in the system. The TP removal was 98% for both loadings, with a concentration in the DP of 0.06 and 0.07 mg/L for L1 and L2, respectively.

Table 3 Total nitrogen (TN) and chemical oxygen demand (COD) removal efficiency for 2017

Parameter		Mean conc. (Inf)	Mean conc. (DP.)	Total loading (Inf)	Total loading (DP)	Mean loading (Inf)	Mean loading (DP)	Loading removal
Units		mg/L	mg/L	kg yr^{-1} ha^{-1}	kg yr^{-1} ha^{-1}	g d^{-1} m^{-2}	mg d^{-1} m^{-2}	%
COD	L1	290 ± 100	21 ± 6	5740	230	3.4	140	96
	L2		19 ± 2	8570	280	5.1	170	97
TN	L1	42 ± 18	3 ± 1	810	23	0.48	10	97
	L2		6 ± 3	1220	90	0.72	50	92
TP	L1	4.1 ± 0.6	0.06 ± 0.01	80	0.6	0.05	0.4	99
	L2		0.07 ± 0.02	120	1.1	0.07	0.6	99

4. Discussion

The validity of the α factor to determine the rate of evapotranspiration is first established by comparing two approaches. The suggested application protocol is then followed to develop a water balance which is then used to determine the wastewater treatment efficiency of the vegetation filter tested.

4.1. Calibration of the α factor

Two approaches for calculating monthly crop coefficients were tested to calibrate the α factor. The monthly approach used the monthly α factors, while the seasonal approach used the average growing season α factor. Both approaches estimated the crop coefficients precisely, especially in the middle of the growing seasons when the ET was maximal (76% of the ET cover between June to August), which indicated that the method could be used to estimate evapotranspiration.

The difference between the results of the method and the known results presented in Frédette et al. (2019)) was greater at the end of the season, but the effect on the total estimate of the ET was minimal for this period (Table 1). This error can be explained by the assumption that the maximum LAI of each year would be representative of that for the whole growing season. The leaf cover does not develop at the same rate in the second year of growth (2016) as in the third (2017) (Frédette et al. 2019). The comparison of only the maximum LAI values could explain that the error was lower between June and September. This suggests that the α method for both approaches, should be limited to similar growth stages and characteristics. Since LAI measurements were time consuming, the calibration suggests that using the maximum LAI, which occurred at the end of June/beginning of July for *Salix miyabeana* in Québec (Frédette et al. 2019), would be appropriate. Stomatal conductance should be measured during the maximum ET peak, between June and August.

The calibration was used to compare two types of means to estimate the α factor, one based on an annual mean transpiration (seasonal approach) and one based on a monthly mean transpiration (monthly approach) calculated from stomatal conductance. The approaches differ in terms of precision and data availability. The calibration results indicate that the seasonal approach can provide good results, especially for the period between June and August. The monthly approach, however, should be used when possible since it was shown to be more precise than the seasonal approach (Fig. 3).

The α factor was not calculated for situations when the crop would be under water stress. Water needs could cause variations in the application of the α method and could lead to an underestimation of the crop coefficients. The FAO-56 suggests a method to adjust the ET according to available water, but prior knowledge of the maximum ET is required (Allen et al. 1998). The effect of water stress with the proposed approach could be investigated.

The α factor could be applied to adjust the design of SWRC as a vegetation filter after installation. Over the years, this could help the operator confirm the evolution of the crop compared to literature data. The α factor method could thus be used for fine-tuning by the treatment system operator, as illustrated in the summary of Fig. 8.

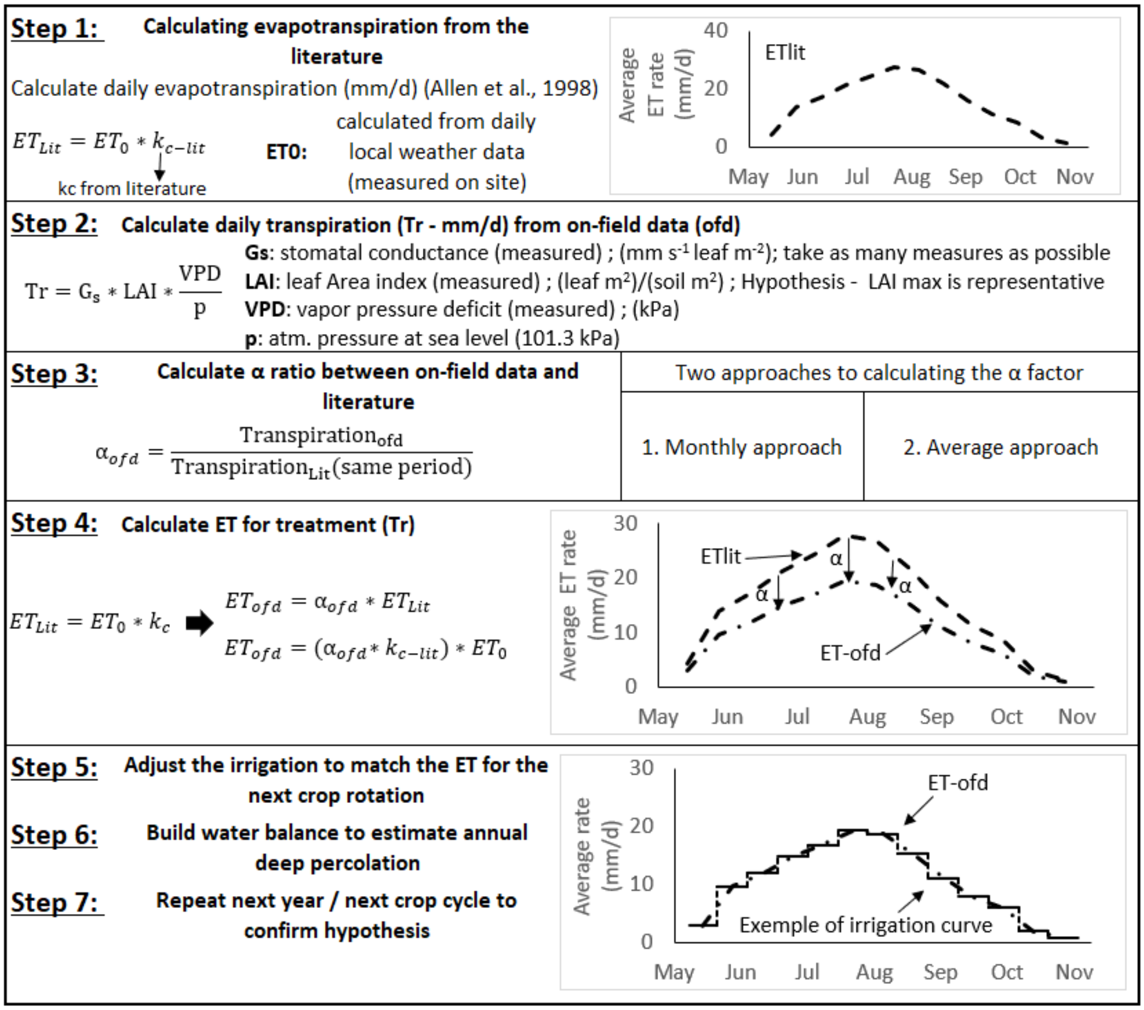

Fig. 8 Summary of the application protocol suggested to use the α method to assist the operation of a short-rotation willow coppice used as a vegetation filter. Notes: ET_{Lit} = evapotranspiration with crop coefficient from literature where ET was estimated from the same species; ET_0 = reference ET from Allen et al. (1998); Tr = transpiration; G_s = stomatal conductance; LAI = leaf area index; VPD = vapor pressure deficit; p = pressure; ET_{ofd}= evapotranspiration with correction from on-field data.

4.2. Application of the α factor method

Primary effluent irrigation increased plant activity, as expected, since more water and nutrients were available. The ratio of photosynthesis to stomatal conductance, the $WUE_{intrinsic}$, should be constant for every treatment, since the same cultivars were planted. The similarity of the $WUE_{intrinsic}$ between this study, between 0.046 and 0.051

μmol/mmol, and the mean for willow cultivars, 0.045 ± 0.016 μmol/mmol (Fischer et al. 2015), supports the validity of the measurements.

The crop coefficients obtained from the ratio applications α_{2016} and α_{2017} were similar, which support the interest in the α method (Table 2). The crop coefficients remained approximate, but the value obtained with this method was more precise than when using the crop coefficient value directly, especially for data obtained at two-week intervals. It was also possible to adjust the ET between L1 and L2, which would not have been possible without using the α method to correct ET according to plant physiological data.

The k_c values obtained were lower than those observed for a second year of growth by Frédette et al. (2019), but higher than those measured by Guidi Nissim et al. (2008). The first study estimated the k_c in wetland, which is subject to clothesline and oasis effects. The second study was conducted for two years with one-year old *Salix alba*. Stem age has an effect on the maximum annual potential yield (Fontana et al. 2016). *Salix miyabeana* also has a higher LAI than *Salix alba* (4.9 and 1.6 m^2/m^2, respectively; *(Tharakan et al. 2005)*. The high crop coefficients estimated with the α method compared to the findings in these studies could be explained by the differences in the age of the plant and the LAI. The ETc rate for loadings 1 and 2 was 9 and 12 mm/d, respectively. These ETc rates were slightly higher than those of 7-12 or 7-9 mm/d reported by Guidi Nissim et al. (2008) and Dimitriou and Aronsson (2004), respectively. The results obtained confirmed that fertilised willows can achieve a high ET, an important factor in vegetation filter design.

Overestimating the ETc would lead to an underestimation of the DP and thus an overestimation of pollutant loading removal. The α method, however, provides a correction to the ETc estimate with the inclusion of local data, which reduces the error of the ETc compared to transposing k_c directly from the literature. The α factors were measured in August and September and thus resulted in some errors for the ET estimated in June (Fig. 5). Measurements should be taken earlier in the summer during the peak growth period to improve accuracy.

4.3. Water balance

The proposed α method made it possible to differentiate between the ET rate for loadings 1 and 2. The estimated water balance suggests that more water could have been irrigated in June and early July, since ET did not reach its full capacity for both treatments. It was estimated that DP was minimal during this period (Fig. 5).

The irrigation that took place in mid-August exceeded the ET capacity, which led to an increase in the estimated DP. The HLRs for this period were 16 mm/d for L1 and 24 mm/d for L2, which were lower than the 73 mm/d (Crites et al. 2014) which is recommended for a soil with the hydraulic conductivity determined at the site (2.0 E-03 cm/s; (Lachapelle-T. et al. 2019). Thus, in this case, the soil infiltration capacity was not limiting, even with the relatively high HLR.

The variation of the annual water balance between data collected in 2016 (Lachapelle-T. et al. 2019) and those of the current study are presented in Table 4, to compare the effect of adjusting the HLR according to the ET rate. The increase of the HLR during the peak of ET led to a slight increase in mean daily HLR (16 to 18 mm/d). The DP for the two years was similar, even if the experiment lasted 111 days in 2016 and 163 days in 2017. The maximum ET for 2016 was lower and could be explained by stem age (one-year-old for 2016, two-year-old for 2017; Guidi Nissim et al. (2008)), and the proposed α method was not applied since no stomatal conductance measurement was taken in 2016.

Table 4 Summary of the seasonal water balance for 2016 (July 20 to November 8; 111 d; Irr = constant) (Lachapelle-T. et al. 2019) and 2017 (May 29 to November 8; 163 d; Irr = varying). Notes: Irr. = irrigation, ETc,adj = adjusted evapotranspiration, DP = deep percolation, ETc, max = maximum potential crop evapotranspiration.

Element		Rain		Irr		$ET_{c,adj}$		DP		$ET_{c, max}$	
Units		mm	mm/d	mm	mm/d	mm	mm/d	mm	mm/d	mm	mm/d
2016	L0	390	4	1510	14	270	2	1630	15	270	2
	L1	390	4	1160	10	470	4	1080	10	530	5
	L2	390	4	1820	16	510	5	1690	15	530	5
2017	L0	580	4	2180	13	670	4	2080	13	730	4
	L1	580	4	1940	12	1490	9	1010	6	1910	12
	L2	580	4	2 960	18	1930	12	1590	10	2300	14

The mean ETc rate for 2017 was double that for 2016. This can be explained by higher crop coefficients due to stem age and the limited period of irrigation in 2016. The irrigation was increased by 2 mm/d between years one and two (approximately 350 mm/growing season), but the estimated annual DP remained approximately the same for both years, caused by over-irrigation at the end of the year. This indicates that increasing irrigation while the ET peaked did not affect the quantity of water released by deep percolation to the groundwater but allowed the cumulative annual volume of water treated to increase. Thus, the HLR should be reduced at the end of September and minimal irrigation should occur in October to minimize the total water discharge to groundwater by leaching.

4.4. Treatment efficiency

Total nitrogen removal (especially NO_x), is the treatment limiting factor for a SRWC on a sandy soil (Crites et al. 2014), based on data obtained in 2016 (Lachapelle-T. et al. 2019) and in 2017 (Fig. 5). The TKN removal remained high (mean of 99%), while the TN began to drop, starting in September. At the same time, over-irrigation as indicated by ET, caused the estimated DP to increase (Fig. 5). The NOx are highly soluble in acidic soils, such as those in Quebec (Havlin et al. 2013). With more DP, more leaching occurred, and the NOx had less time to be denitrified. Moreover, most nutrient uptake (such as NOx) takes place between May and August (Labrecque and Teodorescu 2003). In 2016, soil conditions were not adequate for achieving denitrification until the end of October, and the same pattern may have occurred in 2017 (Lachapelle-T. et al. 2019).

The TN concentration in DP water for L1 did not exceed 7 mg N/L, while that for L2 reached between 6 and 13 mg N/L after mid-September (Fig. 6). There are no nitrite and nitrate discharge standards for land treatment systems that operate by soil infiltration in Quebec. In comparison, the standard for nitrite and nitrate in drinking water is 10 mg N/L (MDDELCC 2015). Nitrite and nitrate concentrations higher than this value were measured in L1 (six occurrences) and L2 (17 occurrences), ranging from 10 to 26 mg N/L and 11 to 42 mg N/L, respectively (Fig. 6). These occurrences took place between July and September for L1 and from the end of June to November for L2 and referred to one sample (not the mean of samples). The number of occurrences and the concentration range were higher in 2017 than in 2016, when only two occurrences ranging from 10 to 12 mg N/L for L1 and nine occurrences ranging from 11 to 23 mg N/L for L2 were reported (Lachapelle-T. et al. 2019). The higher number of occurrences indicated that the increase of the HLR resulted in a greater variation between samples, but the mean results remained under the NOx drinking water standard.

Decreasing the HLR at the end of the season, especially for L2, could lower such NOx occurrences (Fig. 7). As a result of its higher loading, L2 had a higher NOx concentration in DP than L1 throughout the entire 2017 season. This highlights how important controlling the HLR is for treatment efficiency, and how on-site measurement of ET can assist for that matter.

The higher TN concentration (Fig. 6) and water balance (Fig. 5) results can explain why a drop in TN removal was observed in September 2017 (Fig. 7). Despite a difference in TN concentrations (relative removal), loading removal was similar for L1 and L2 (absolute removal) until September, when DP increased significantly, as observed by Jonsson et al. (2004). The present study observed the same pattern for nitrogen as for the parameters studied by Jonsson et al. (2004) which had more ambiguous results for TN. The difference in the results could be explained by the low concentration input compared to that of the present study (42 mg N/L for this study compared to 3 mg/L for Jonsson et al. (2004)).

The COD concentration in the DP water was similar for L1 and L2 (21 vs 19 mg COD/L, respectively). The low standard deviation, 6 for L1 and 2 for L2, indicates small variations over the season, even with an increase of the HLR. These low concentrations can be explained by the low organic matter loadings of 19 and 28 kg BOD_5 ha^{-1} d^{-1} for L1 and L2, respectively, compared to 50 – 500 kg BOD_5 ha^{-1} d^{-1} as recommended for slow infiltration land application systems (US EPA 2006). COD annual loading removal of 96% for both treatments was consistent with those reporting for the first year of this study (Lachapelle-T. et al. 2019). Organic matter removal was not limiting in this experiment and a higher HLR did not affect the DP COD concentration.

The TP concentration in the DP water was similar for L1 and L2. The TP loading removal was nearly complete (98% removal) and was as high in 2017 as in 2016 (Lachapelle-T. et al. 2019). TP in soil infiltration systems is expected to be removed by plants and fixed in soil (MDDELCC 2001). Phosphorus immobilization in soil could, however, be greatly reduced if the soil becomes saturated, which should occur after a few years of operation (Paranychianakis et al. 2006).

COD and nutrients leaching into the groundwater could take place during the winter period due to mineralization processes. Groundwater quality monitoring would allow to assess the significance of this process.

Conclusion

This study aimed to develop a method for estimating ET to optimize the wastewater treatment capacity of a short rotation willow coppice (SRWC) vegetation filter by adjusting the seasonal hydraulic loading rate (HLR). The project was carried out on a two-hectare willow crop for two years. A new α method was proposed to estimate ET_c, which made it possible to evaluate the effect of increasing the HLR during periods of high ET.

The conclusions of this study are:

- An α factor calculated from the ratio of the transpiration reported in the literature and the transpiration estimated from field data can be used to adjust evapotranspiration calculations for fertilized zones with approximately the same growth stage. This approach could be applied to fine-tune the HLR on a SWRC used as a vegetation filter, after establishment;
- Irrigation with a primary municipal effluent significantly increased willow stomatal conductance and photosynthesis ($p < 0.05$), but intrinsic water use efficiency remained stable. The estimated α factor between the transpiration reported in the

literature and the transpiration estimated from field were 0.69 for loading 1 (L1) and 0.83 for loading 2 (L2);

- Estimated deep percolation (DP) was minimized when irrigation took place during periods of high evapotranspiration. Excessive irrigation at the end of 2017 resulted in an increase in estimated DP;
- High total nitrogen removal was estimated even at a hydraulic loading rate as high as 2.4 cm/d for L2 in 2017;
- Over-irrigation starting September, while the ET was low, caused high DP and nitrogen leaching. HLR and nitrogen removal were the limiting parameters of the SWRC vegetation filters.
- Organic matter removal (COD) and total phosphorus removal (TP) were high (96%, 98%, respectively) at both loadings L1 and L2;
- Adjusting the HLR according to the evapotranspiration rate capacity would make it possible to optimize the treatment capacity in terms of quantity of water treated and quality of percolation water.

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