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4 **Effects of Evapotranspiration on Treatment Performance in Constructed Wetlands:**
5 **Experimental Studies and Modeling**
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Abstract

Evapotranspiration (ET) can affect treatment performance in constructed wetlands by enhancing constituent transport through the hydrosol where treatment reactions occur. Additionally, ET can decrease volumetric flow thereby increasing hydraulic retention time and increasing concentrations of dissolved constituents. This research aims to assess the net effects of water loss attributed to ET on constructed wetland performance and determine the significance of plant transpiration on vertical transport of constituents. A flowing wetland lysimeter constructed using 265-L storage containers filled with sand and *Typha latifolia* was used to record ET and determine crop coefficient during summer 2011. Results indicate that ET from the lysimeter was 2.5 times greater than calculated reference ET ($K_c = 2.5$; $R^2 = 0.96$). The calculated crop coefficient was used in conjunction with a first-order tank-in-series model to predict removal of a conservative constituent ($k = 0.2 \text{ d}^{-1}$) and readily treatable constituent ($k = 1.2 \text{ d}^{-1}$) in a constructed wetland (20 cm and 40 cm water depths, 4-day nominal HRT, and 100 mg L^{-1} constituent loading) operating under a range of ET (0, 10, 20, and 30 mm d^{-1}). The model predicts that removal efficiency of the conservative constituent decreases with increasing ET, while removal efficiency of the readily treatable constituent increases with increasing ET. In addition, eight vertical tracer tests were performed on wetland cells with either trimmed or untrimmed *T. latifolia* to measure transport time of tracer solution from the water surface to a depth of 5 cm. Mean tracer arrival time differed significantly ($p = 1.2 \times 10^{-8}$) between the untrimmed and trimmed cells (104 minutes versus 450 minutes,

61 respectively) demonstrating that plant transpiration contributes significantly to vertical
62 flow through hydrosol.

63 Keywords: Constructed Wetlands, Evapotranspiration, Tracer Tests, Modeling, Typha
64 Latifolia, Cattails

1. Introduction

Water loss in constructed wetland treatment systems (CWTSS) occurs primarily through the combined effects of open water evaporation and plant transpiration, collectively termed evapotranspiration. Because CWTSS are typically constructed with a lined bottom to prevent infiltration of contaminated water to underlying soil, evapotranspiration is a key component of the water balance. Evapotranspiration is driven primarily by the transformation of insolation energy to latent heat of vaporization of liquid water.

Numerous studies have been performed to quantify evapotranspiration from wetlands containing *Typha latifolia* (i.e. broadleaf cattails) with conflicting results attributed to differing measurement methods and lysimeter designs (Allen and Prueger, 1992; Allen et al., 1997; Anderson and Idso, 1987; Idso and Anderson, 1988; Otis, 1914; Idso, 1981; Snyder and Boyd, 1987; Towler et al., 2004). As explained by Idso and Anderson (1988), evapotranspiration can be influenced by the “oasis effect” (Shaw, 1967) resulting in elevated evapotranspiration from isolated, small stands of vegetation compared to large expanses of vegetation. Incoming latent heat from surrounding dry fetch is advectively exchanged through the periphery of isolated stands of vegetation, leading to an increase in incoming energy and corresponding increase in evapotranspiration (Idso and Anderson, 1988; Towler et al., 2004). Evapotranspiration is also dependent on regional meteorological factors including air temperature, relative humidity, solar radiation, and wind speed, as well as CWTSS design features including plant species diversity and density (Allen et al., 1998).

Changes in volumetric flow attributed to evapotranspiration can alter CWTS treatment performance by removing water from the system (thus increasing hydraulic retention time) and increasing concentrations of dissolved constituents. Differences in evapotranspiration attributed to CWTS size, climatic region, and plant selection can lead to inaccurate predictions of treatment performance when using previously determined removal rate coefficients. Because removal performance data collected from small, pilot-scale CWTS studies may be applied to designing full-scale CWTSs in different climatic regions, the extent to which differing evapotranspiration can affect treatment is of interest.

Additionally, because both the inflow and outflow of free water surface (FWS) CWTSs are located above the hydrosol, a decreasing hydraulic head with depth is needed to advectively transport targeted constituents to the hydrosol where treatment by specific redox-driven reactions occurs (Kadlec, 1999; Kadlec and Wallace, 2009; Martin and Reddy, 1997; Martin et al., 2003). Previous studies suggest that plant transpiration plays a role in establishing a vertical hydraulic gradient within wetland hydrosol (Martin et al., 2003). The extent to which constituents are transported advectively can be estimated through a transpiration to evapotranspiration ratio based on the assumption that water lost through plant transpiration must move through the root zone (Kadlec and Wallace, 2009). However, root density and location can affect flow through the hydrosol and water column (Figure 1). Therefore, the ability of plant transpiration to vertically transport constituents warrants investigation to determine if FWS CWTSs are capable of supporting treatment by redox-driven reactions in the hydrosol.

The objectives of this paper are to (1) determine the crop coefficient for a small-stand, pilot-scale CWTS, (2) predict differences in constructed wetland treatment performance attributed to evapotranspiration-driven water-loss, and (3) measure the effects of plant transpiration on vertical flow of constituents. Completion of these objectives provides a fundamental understanding of the effects of evapotranspiration on treatment performance in FWS CWTSs containing *T. latifolia*.

2. Materials and Methods

2.1 Pilot-scale Crop Coefficients for Typha latifolia

T. latifolia evapotranspiration (ET_c) was monitored using four 0.5-m² containerized wetland troughs connected in series to form a 2-m² constant-head lysimeter with dimensions similar to pilot-scale CWTSs used in many previous studies (e.g Dorman et al., 2009; Horner et al., 2012; Kanagy et al., 2008; Spacil et al., 2011). The lysimeter consisted of four 265-L troughs, each filled to a depth of 45 cm with sandy river sediment collected from nearby 18-mile Creek (Clemson, SC) and planted to field density (approximately 20 plants per trough or 10 plants per m²) with *T. latifolia* collected from nearby aquaculture ponds. The four troughs were connected in series with 2.5-cm diameter polyvinyl chloride (PVC) piping and arranged for gravity flow, with fixed overflow pipes installed in each trough to maintain a constant head and water-depth of 15 cm (Figure 2). Water was supplied to the first trough at a constant rate of 6 L h⁻¹ (6x10⁶ mm³ h⁻¹) by a Fluid Metering Inc. ® pump (QG400). The lysimeter was allowed to mature for approximately 3 years before any ET_c data were collected. The plants were fertilized periodically to promote vigorous growth. The lysimeter remained outdoors in

Clemson, SC (34.69° N, 82.81° W) for the duration of the experiment from July through August of 2011.

Volumetric outflow of the lysimeter was monitored using a RainWise® Inc. tipping bucket rain gauge placed under the outflow pipe of the last trough of the lysimeter (Figure 2). The rain gauge was connected to a RainWise® RainLog digital data logger with 256 kB of non-volatile memory capable of recording flow information at a resolution of 1 minute. The rain gauge was calibrated prior to the experiment using ten timed, one-minute intervals of a constant 6 L h⁻¹ flow rate provided by the FMI QG400 pumps. Hourly volumetric outflow data were recorded and downloaded for three 5- to 7-day intervals in July and August after the plants had reached maturity.

ET_c (mm h⁻¹) was calculated as the difference between the volumetric inflow and outflow divided by the surface area of the lysimeter for data collected during dry periods with no precipitation (Eqn. 1).

$$ET_c = \frac{Q_{in} - Q_{out}}{SA} \quad \text{Eqn. 1}$$

Where Q_{in} is volumetric inflow of the lysimeter (6x10⁶ mm³ h⁻¹), Q_{out} is measured volumetric outflow of the lysimeter (mm³ h⁻¹), and SA is measured surface area of the lysimeter (2x10⁶ mm²).

Small-stand crop coefficients for *T. latifolia* were determined using linear regressions of hourly ET_c measured from the lysimeter and hourly reference evapotranspiration (ET_o). ET_o values were calculated using the FAO-56 Penman-Monteith method (Allen et al., 1998; Penman 1963) from meteorological data collected with an on-site Davis Instruments® Vantage Pro 2 weather station. The FAO-56

Penman-Monteith method (Eqn. 2) was used to calculate ET_o for a reference crop with an assumed crop height of 0.12 m, fixed surface resistance of 70 s m^{-1} , and albedo of 0.23. This method was selected because it meets the precision required for calculating crop coefficients using readily acquired meteorological data (e.g. temperature, dew point, wind speed, and solar radiation) and is commonly used in other evapotranspiration studies (e.g. Allen et al., 1998).

$$ET_o = \frac{(0.408)\Delta(R_n) + \gamma \frac{37}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad \text{Eqn. 2}$$

where ET_o is reference evapotranspiration (mm h^{-1}) calculated from meteorological data; Δ is slope of the saturation vapor pressure temperature relationship ($\text{kPa } ^\circ\text{C}^{-1}$, $1 \text{ kPa} = 1 \times 10^3 \text{ pascals}$); R_n is measured net radiation ($\text{MJ m}^{-2} \text{ h}^{-1}$, $1 \text{ MJ} = 1 \times 10^6 \text{ joules}$); γ is psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$); T is measured air temperature ($^\circ\text{C}$); u_2 is wind speed (m s^{-1}) measured at a height of 2 m; $(e_s - e_a)$ represents vapor pressure deficit of the air (kPa); e_s is saturation vapor pressure of the air (kPa); e_a is vapor pressure of the air (kPa). Values for Δ , γ , e_s , and e_a were calculated from meteorological data collected with the on-site weather station (Table 1).

Crop coefficients (K_c ; Eqn.3) can be used to predict evapotranspiration of a plant species from measured meteorological data (ET_o), and therefore were used to predict differences in evapotranspiration between large-stand ($>1 \text{ Hectare}$) and small-stand (e.g. pilot-scale) wetlands.

$$K_c = \frac{ET_c - E_b}{ET_o} \quad \text{Eqn. 3}$$

where K_c is crop coefficient (unitless); ET_c is measured *T. latifolia* evapotranspiration (mm h⁻¹); ET_o is reference evapotranspiration (mm h⁻¹); and E_b is baseline evaporation measured (mm h⁻¹).

Baseline evaporation is included in the calculation of ET_c to account for incoming latent heat from the inflow (Kadlec, 2006). K_c and E_b were determined for the small-stand *T. latifolia* in lysimeter using a linear regression of ET_c versus ET_o (Eqn. 4).

$$ET_c = (ET_o \times K_c) + E_b \quad \text{Eqn. 4}$$

The calculated lysimeter K_c was compared with the large-stand wetland K_c value (Abtew and Obeysekera, 1995) to predict differences in water loss expected between pilot-scale and full-scale CWTSSs.

2.2 Analytical Evapotranspiration Performance Model

A first-order, one-dimensional, steady-state model for estimating the effects of evapotranspiration on treatment performance of a CWTS was derived from a conceptual, serial connection of continuously stirred tank reactors (CSTRs), also known as the tank-in-series (TIS) model proposed by Levenspiel (1972). Treatment performance was evaluated on the basis of CWTS removal extent (i.e. final outflow constituent concentration) and removal efficiency (i.e. percentage of constituent removed from inflow to outflow by the CWTS). The TIS model was selected because it can be used to recreate the hydrodynamics of FWS wetlands when the number of CSTRs connected in series (N) is calibrated to tracer test breakthrough data (Kadlec and Wallace, 2009). Other models utilizing conceptual plug-flow-reactors (PFRs) and plug-flow-reactors with dispersion (PFD) have been suggested for CWTSSs, but may not be ideal because they are

not accurate within the mixing ranges for FWS CWTSs identified through tracer tests (Kadlec and Wallace, 2009; Levenspiel, 1972). In addition, the TIS model can be calculated as a series of mass balances using simple algebra.

The TIS model used to determine treatment performance consisted of 16 CSTRs (N = 16) of unit area connected in series. This N value was selected to model a CWTS with four wetland cells and is based on the mean N value previously determined for single FWS CWTS cells (N = 4.1; Bavor et al., 1988; Kadlec, 1994; Kadlec and Wallace, 2009; Nolte and Associates, 1998; Wang and Jawitz, 2006). The model was derived from the wetland mass balance and first-order removal kinetics (Eqn. 5).

$$Q_{in}C_{in} - Q_{out}C_{out} = kC_{out}(A \times d) \quad \text{Eqn. 5}$$

where Q_{in} is volumetric inflow to the CSTR ($\text{m}^3 \text{d}^{-1}$); C_{in} is constituent concentration of Q_{in} (g m^{-3}); Q_{out} is volumetric outflow of the CSTR ($\text{m}^3 \text{d}^{-1}$); C_{out} is constituent concentration of Q_{out} (g m^{-3}); k is volumetric first-order removal coefficient (d^{-1}); A is surface area of the CSTR (m^2); and d is water depth of the CSTR (m).

Assuming a unit area for A , rearrangement of Eqn. 5 yields the equation:

$$q_{in}C_{in} - q_{out}C_{out} = kC_{out} \times d \quad \text{Eqn. 6}$$

where q_{in} is inflow hydraulic loading (m d^{-1}); and q_{out} is outflow (m d^{-1}).

Eqn. 6 rearranged for C_{out} :

$$C_{out} = \frac{q_{in}C_{in}}{q_{out} + (k \times d)} \quad \text{Eqn. 7}$$

Because q_{out} is the difference between q_{in} and water loss due to plant evapotranspiration (ET_c), Eqn. 7 can be rewritten:

$$C_{out} = \frac{q_{in}C_{in}}{q_{in} - ET_c + (k \times d)} \quad \text{Eqn. 8}$$

217 Or in discrete form to allow for calculation of C_{out} for each of the 16 CSTRs (i from 1 to
218 16) in the TIS model:

$$219 \quad C_{(i)} = \frac{q_{(i-1)}C_{(i-1)}}{q_{(i-1)} - \frac{ET_c}{16} + (k \times d)} \quad \text{Eqn. 9}$$

220 where $c_{(i)}$ is outflow constituent concentration of CSTR i (g m^{-3}); $c_{(i-1)}$ is inflow
221 constituent concentration of CSTR i (g m^{-3}); and $q_{(i-1)}$ is inflow hydraulic loading (m d^{-1}).

222 Eqn. 9 was used to model removal of a conservative constituent (e.g. boron,
223 chloride, etc.) with a volumetric first-order removal coefficient of 0.2 d^{-1} and readily
224 treatable constituent (e.g. nitrate, oil and grease, etc.) with a volumetric first-order
225 removal coefficient of 1.2 d^{-1} in both shallow (20-cm water depth) and deep (40-cm water
226 depth) FWS CWTSSs operating with a 4-day nominal HRT under a range of ET_c from 0 to
227 30 mm d^{-1} (Table 2). ET_c values selected for the model were based on pilot-scale K_c
228 measured from the lysimeter and K_c reported in previous studies for large-scale wetlands
229 containing *T. latifolia* and range from baseline evapotranspiration (0 mm d^{-1}) to arid
230 desert reference evapotranspiration (12 mm d^{-1} ; Einesr et al., 2010). Predictions from the
231 model were compared to demonstrate the potential effects of evapotranspiration on
232 removal efficiency of conservative and readily treatable constituents. In order to isolate
233 and examine the effects of changes to the water balance attributed to evapotranspiration
234 on treatment performance, removal rate coefficients used in the model were assumed to
235 be unaffected by changes in evapotranspiration.

236 *2.3 Vertical Tracer Tests*

237 The effect of *T. latifolia* transpiration on vertical transport of dissolved
238 constituents in bench-scale CWTSSs was measured by vertical tracer tests. These tests

monitored hydrosol electrical conductivity to detect differences in dissolved tracer arrival between wetland cells containing mature plants and cells containing trimmed plants. Eight 20-L buckets were prepared as bench-scale wetland cells by filling each with approximately 20 cm of sandy sediment and approximately 8 *T. latifolia* plants. The buckets were watered and fertilized regularly and stored in a climate-controlled greenhouse for 9 months to promote plant maturation. After the maturation period, *T. latifolia* in 4 randomly selected cells were trimmed to a height of 30 cm above the hydrosol (corresponding to 5 cm above the waterline) immediately prior to each tracer test to eliminate plant transpiration.

Surface water electrical conductivity data collected from each wetland cell were used to formulate tracer solutions containing amounts of dissolved sodium chloride needed to yield conductivity readings ten times greater than readings from the surface water. This strength of tracer solution was selected to allow accurate resolution of tracer arrival time.

Eight individual tracer tests (4 with untrimmed plants and 4 with trimmed plants) were performed by placing a pair of HANNA Instruments® HI 98331 stainless steel conductivity probes 5 cm below the hydrosol surface of each cell. Prepared tracer solution was then added to the cell by a FMI® QG400 pump at a rate of 12 L h^{-1} . After 5 minutes, a second QG400 pumping at a rate of 12 L h^{-1} was connected to the system at a height of 25 cm above the hydrosol surface to remove excess tracer solution, maintaining a constant head. This method allowed tracer solution to be added gently, attempting to prevent vertical flow disturbances while allowing circulation of the tracer solution.

Hydrosoil conductivity was measured every 5 minutes until increased electrical conductivity readings were detected for a minimum of 3 consecutive measurements at each probe. Mean arrival times for the four untrimmed and four trimmed cells were compared using Welch's t-test to determine if plant transpiration significantly altered flow through hydrosoil of the wetland cells ($\alpha=0.05$). If a significant difference in tracer arrival time between the untrimmed and trimmed wetland cells occurred, then it was concluded that plant evapotranspiration plays a role in transporting constituents in FWS CWTSS through the hydrosoil where specific redox conditions for treatment reactions occur.

3. Results

3.1 Pilot-scale Crop Coefficients for Typha latifolia

A diurnal pattern of ET_c was observed in the lysimeter, with lowest evapotranspiration occurring in the early morning (approximately 0.2 mm h^{-1}) and greatest evapotranspiration occurring in the late afternoon (approximately 2 mm h^{-1} ; Figure 3). A similar diurnal pattern was observed for the calculated ET_o . ET_o was consistently lower than ET_c throughout the day and was slightly negative (approximately -0.02 mm h^{-1}) in the early morning when air temperature was below the dew point. Over the duration of the experiment, measured mean air temperature was 27.4°C , mean dew-point was 21.4°C , mean wind speed was 0.26 m s^{-1} , and mean solar radiation was 260 W m^{-2} (Table 3).

Linear regression of ET_c versus ET_o for the three periods during which evapotranspiration was monitored in July and August (Figure 4) yielded a K_c value of 2.5

($R^2 = 0.96$) which is greater than the K_c of 1.0 ($R^2 = 0.86$) reported for large wetlands (Abtew and Obeysekera, 1995). Baseline evaporation (E_b) identified from the intercept of the linear regression was 0.3 mm h^{-1} . A comparison of the measured volumetric outflow from the lysimeter with theoretical volumetric outflow predicted from ET_o , K_c , E_b , and SA indicates a close match of observed and predicted evapotranspiration (Figure 5).

3.2 Analytical Evapotranspiration Performance Model

Predictions from the TIS model (Eqn. 9) indicate changes in treatment performance associated with differing ET_c from 0 to 30 mm d^{-1} (Figure 6). Treatment performance of a conservative constituent ($k = 0.2 \text{ d}^{-1}$) is predicted to be negatively affected by increasing ET_c at water depths of both 20 cm and 40 cm (Figures 6A, 6B). As ET_c increased from 0 to 30 mm d^{-1} , concentration removal efficiency of the conservative constituent decreased from 54.2 to 25.4% at the 20-cm water depth and from 54.2 to 43.9% at the 40-cm water depth.

Treatment performance of a readily treatable constituent ($k = 1.2 \text{ d}^{-1}$) is predicted to be marginally enhanced by increasing ET_c at both water depths (Figures 6C, 6D). As ET_c increased from 0 to 30 mm d^{-1} , concentration removal efficiency of the readily treatable constituent increased from 98.5 to 99.0% at the 20-cm water depth and from 98.5 to 99.0% at the 40-cm water depth.

3.3 Vertical Tracer Tests

Tracer arrival times were consistently less in the wetland cells containing untrimmed plants compared to the cells containing trimmed plants (Figure 7). Mean tracer arrival time from all tracer tests was 104 minutes ($\sigma = 25$ minutes) in the

untrimmed cells and 450 minutes ($\sigma = 57$ minutes) in the trimmed cells. Comparison of mean arrival times in the untrimmed and trimmed cells indicates that tracer arrival times were significantly different ($p = 1.2 \times 10^{-8}$).

4. Discussion

Results from this study support the wetland oasis effect described by Idso and Anderson (1988) where small, isolated wetlands have greater evapotranspiration than large-stand wetlands. The calculated lysimeter crop coefficient ($K_c = 2.5$ $R^2 = 0.96$; Figure 4) for the 2-m² lysimeter used in this study was more than two times greater than the crop coefficient measured by Abtew and Obeysekera ($K_c = 1.0$ $R^2 = 0.86$; 1995) for a 549-hectare *T. latifolia* wetland located in South Florida. Generally, evapotranspiration from pilot-scale CWTs is expected to be greater than full-scale CWTs. The crop coefficient measured in this study applies to mature plants and can be used to predict evapotranspiration from small pilot-scale systems located in different climatic regions where reference evapotranspiration is known or can be measured.

Lysimeter measurements indicate that volumetric outflow decreased to approximately 1.2 L h⁻¹ during peak evapotranspiration in the late afternoon (Figure 5), corresponding to an 80% decrease in volume from inflow to outflow. Over the course of each 24-hour period, the 6 L h⁻¹ volumetric inflow decreased to a mean volumetric outflow of 4.2 L h⁻¹, indicating a daily volumetric loss of 30% of inflow. A 30% decrease in water volume corresponds to a 43% increase in concentration of constituents as predicted by the law of mass conservation. However, a 30% loss of volumetric inflow is

326 predicted to increase nominal HRT by approximately 20% based on the ratio of system
327 volume to volumetric inflow.

328 Differences in CWTS treatment performance attributed to increased
329 evapotranspiration are predicted by the model to depend on both water depth and
330 constituent removal rate coefficients. Because increased evapotranspiration is predicted
331 to have a deleterious effect on removal efficiency of conservative constituents,
332 evapotranspiration can lead to excessive salinity when CWTSs are used to treat brackish
333 or brine waters containing high concentrations of ions such as sodium and chloride. As
334 predicted by the model (Figure 6), water depth can be increased to mitigate the effects of
335 evapotranspiration; however, removal of targeted constituents can be altered by a change
336 in water depth due to changes in treatment conditions (Gillespie et al., 2000).

337 Because removal efficiency of readily treatable constituents is predicted to be
338 only marginally enhanced by increased evapotranspiration, lengthening of HRT caused
339 by evapotranspiration can overcome the increased concentration of constituents due to
340 water loss. As a result, properly designed CWTSs with sufficiently high removal rate
341 coefficients ($\sim 1.2 \text{ d}^{-1}$) for targeted constituents are predicted to be resilient to changes in
342 water loss due to evapotranspiration and can be modeled without considering changes in
343 the water balance caused by evapotranspiration.

344 Results from tracer tests verify the transpiration-driven vertical flow path
345 described by Martin et al. (2003). Therefore, it is likely that redox-driven reactions in
346 FWS CWTS hydrosoil (e.g. dissimilatory sulfate reduction and denitrification) can
347 contribute to removal of targeted constituents that require reducing conditions. Further

research is required to determine the flux of water through hydrosol of FWS wetlands by plant transpiration; however, maximum flux will be bound by total measured plant transpiration. Additionally, changes in flow through the hydrosol under different evapotranspiration can contribute to changes in performance and warrants further investigation.

5. Conclusions

The crop coefficient for the 2-m² lysimeter was determined to be 2.5 times greater ($K_c = 2.5$, $R^2 = 0.96$) than the crop coefficient previously reported for a large-stand *T. latifolia* wetland ($K_c = 1.0$, $R^2 = 0.86$). The difference in the crop coefficient measured for the lysimeter used in this study and large-stand *T. latifolia* wetlands supports the oasis effect described in previous studies. As evapotranspiration increases from 0 to 30 mm d⁻¹, the TIS model predicts that **concentration** removal efficiency for conservative constituents is negatively affected (from 54.2 to 25.4% at 20-cm water depth), while **concentration** removal efficiency for readily treatable constituents is marginally enhanced (from 98.5% to 99.5% at 20-cm water depth). In addition, plant transpiration significantly ($p = 1.2 \times 10^{-8}$) enhanced vertical transport of constituents through FWS CWTS hydrosol. Results from the lysimeter study and TIS model may be applied to predicting differences in evapotranspiration and performance between pilot-scale and full-scale CWTSs and among CWTSs located in different climatic regions. Results from the vertical tracer tests demonstrate the importance of plant transpiration on vertical flow of constituents in FWS CWTSs and verify that constituents can be transported vertically through the hydrosol where redox-driven treatment reactions occur.

Acknowledgement

We gratefully acknowledge funding provided by Clemson University and the United States Department of Energy (USDOE) through the National Energy Technology Laboratory under Award Number DE-NT0005682. This article was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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- 482 Figure 1. Excavated *T. latifolia* with root mass showing root growth above the hydrosol
483 surface. Arrows indicate hypothesized flow path generated by plant transpiration.
- 484 Figure 2. Schematic diagram of the 2-m² lysimeter showing all four 0.5-m² containerized
485 wetland troughs connected in series. Water was supplied to the first trough at a
486 rate of (6 L h⁻¹) and volumetric outflow was recorded by a RainWise® tipping
487 bucket rain gauge located at the outflow of the last trough.
- 488 Figure 3. Hourly plot of measured evapotranspiration (ET_c) and calculated reference
489 evapotranspiration (ET_o). Evapotranspiration was lowest during the evening and
490 greatest in the late afternoon.
- 491 Figure 4. Linear regression of ET_c versus ET_o . The slope value of 2.5 yields the crop
492 coefficient (K_c) for pilot-scale CWTSSs containing *T. latifolia*.
- 493 Figure 5. Comparison of measured volumetric outflow from the lysimeter and volumetric
494 outflow predicted using ET_o , K_c , and E_b . Mean volumetric outflow from the
495 lysimeter during this 4-day period was 4.2 L h⁻¹.
- 496 Figure 6. TIS model results showing outflow concentrations of the 16 CSTRs during
497 evapotranspiration from 0 to 30 mm d⁻¹ for: (A) Conservative constituent (0.2 d⁻¹)
498 at a water depth of 20 cm, (B) conservative constituent at a water depth of 40 cm,
499 (C) readily treatable constituent (1.2 d⁻¹) at a water depth of 20 cm, (D) readily
500 treatable constituent at a water depth of 40 cm. As evapotranspiration increased
501 from 0 to 30 mm d⁻¹, concentrations of the conservative constituent at outflow
502 from the final CSTR (16) increased at water depths of both 20 and 40 cm,
503 indicating a decrease in treatment performance (A and B). Treatment performance

504 of the readily treatable constituent was marginally enhanced as evapotranspiration
505 increased from 0 to 30 mm d⁻¹ for both water depths as shown by the difference
506 in outflow concentrations of the final CSTR (C and D).

507 Figure 7. Measured tracer arrival times at each of the two conductivity probes (P1 and
508 P2) for both untrimmed and trimmed wetland cells. The arrival times were
509 consistently lower in the untrimmed cells than the trimmed cells indicating
510 transpiration-driven vertical transport of tracer through hydrosol.

Figure 1.

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513 Figure 2.
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Figure 3.

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524 Figure 7.

Table 1. Calculations for reference evapotranspiration equation (Eqn. 2)			
Parameter	Symbol	Units	Formula
Slope of saturation vapor pressure curve	Δ	kPa °C ⁻¹	$\frac{4098 \left[0.6108 \exp \left(\frac{17.27 \times T_{mean}}{T_{mean} + 237.3} \right) \right]}{(T_{mean} + 237.3)^2}$
Psychrometric constant	γ	kPa °C ⁻¹	$(6.65 \times 10^{-2}) \times P$
Saturation vapor pressure	e_s	kPa	$\frac{0.6108 \exp \left(\frac{17.27 \times T_{max}}{T_{max} + 237.3} \right) - 0.6108 \exp \left(\frac{17.27 \times T_{min}}{T_{min} + 237.3} \right)}{2}$
Actual vapor pressure	e_a	kPa	$0.6108 \exp \left(\frac{17.27 \times T_{dew}}{T_{dew} + 237.3} \right)$

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Table 2. Input parameters for scenarios modeled using a TIS receiving a hydraulic loading to maintain a nominal hydraulic retention time of 4 days and a constituent concentration loading of 100 g m^{-3} .

Scenario	Evapotranspiration (mm d^{-1})	Water Depth (m)	Removal Rate Coefficient (d^{-1})
1	0	0.2	0.2
2	10	0.2	0.2
3	20	0.2	0.2
4	30	0.2	0.2
5	0	0.2	1.2
6	10	0.2	1.2
7	20	0.2	1.2
8	30	0.2	1.2
9	0	0.4	0.2
10	10	0.4	0.2
11	20	0.4	0.2
12	30	0.4	0.2
13	0	0.4	1.2
14	10	0.4	1.2
15	20	0.4	1.2
16	30	0.4	1.2

Table 3. Measured meteorological conditions during experiment period (July and August of 2011).

Parameter	Mean	Standard Deviation	Range
Temperature (°C)	27.4	4.6	16.1- 38.4
Dew-point (°C)	21.4	2.6	11.7 - 26.6
Windspeed (m s ⁻¹)	0.26	0.41	0.00 - 2.24
Solar Radiation (w m ⁻²)	260	331	0 - 1020

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