# Hydraulic performance of small free water surface constructed wetlands treating sugar factory effluent in western Kenya

Hristina Bodin and Jesper Persson

## ABSTRACT

This study investigated, using a lithium salt tracer, how macrophyte species and hydraulic loading rate (HLR) of wastewater influenced hydraulics in constructed wetlands (CWs). Four pilot-scale CWs received 45 mm day$^{-1}$ of pre-treated sugar factory effluent and another four received 110 mm day$^{-1}$. Half the CWs were planted with *Cyperus papyrus* and half with *Echinochloa pyramidalis*. Results showed a significant negative connection between tracer mass recovery and wetland water leakages. Also, a significant negative relationship between active wetland water volume and macrophyte density was detected. Further, a significant effect of HLR on mass removal rates of $NH_4^+$-N was observed. However, no significant effect of either HLR or macrophyte species on wetland hydraulic parameters was found.

**Key words** | constructed wetland, *Cyperus papyrus*, *Echinochloa pyramidalis*, hydraulic loading rate, hydraulic tracer study, vegetation

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## NOTATION

| | |
|---|---|
| HRT | hydraulic residence time [h] |
| HLR | hydraulic loading rate [mm h$^{-1}$] or [mm day$^{-1}$] |
| $f(t)$ | residence time distribution (RTD) function [h$^{-1}$] |
| $t_n$ | nominal hydraulic residence time [h] |
| $Q$ | water flow rate [m$^3$ h$^{-1}$] |
| $C(t)$ | exit tracer concentration [g m$^{-3}$ = mg l$^{-1}$] |
| $t$ | time of sample [h] |
| d$t$ | change in time between samples [h] |
| $V_{total}$ | total wetland water volume [m$^3$] |
| $V_{effective}$ | total active wetland volume [m$^3$] |
| $t_{mean}$ | mean hydraulic residence time of RTD function [h] |
| $t_{peak}$ | maximum value of RTD function [h] |
| $\sigma^2$ | variance of RTD function [h$^2$] |
| $e$ | effective volume ratio [–] |
| $\lambda$ | hydraulic efficiency [–] |
| $N$ | number of tanks in tanks-in-series model [–] |
| $E_{PAN}$ | pan evaporation [mm day$^{-1}$] |
| $ET_0$ | potential evapotranspiration [mm day$^{-1}$] |
| $ET$ | wetland evapotranspiration [mm day$^{-1}$] |
| $k$ | empirical pan coefficient [–] |

doi: 10.2166/nh.2012.133

## INTRODUCTION

Constructed wetlands (CWs) are generally recognized as low-cost water purification systems and nutrient sinks that improve the quality of downstream surface waters (Kadlec & Wallace 2009). However, many of the wetlands in operation today are not performing as effectively as they could, due to limits and anomalies in models used to design them (Fisher 1990; Kadlec 2000; Konnerup *et al.* 2009).

Wastewater pollutants are transformed and reduced in wetlands through numerous interconnected physical, chemical and biological processes. The significance of wetland hydraulics becomes obvious when the basic facts about these pollutant reduction processes are considered. Many of these processes start to occur at the surfaces of the wetland vegetation, detritus and substrate. Thus, the efficiency of the removal processes is above all related to the degree of contact between the wastewater and the reactive surfaces in the wetland. Therefore, understanding the characteristics of wastewater flow patterns and residence time (hydraulics and hydrology) is the key to designing optimized wetlands with regard to both treatment performance and land utilization, i.e. size and geometry of wetlands (Kadlec 1994, 2000; Werner & Kadlec 2000; Martinez & Wise 2003).

To better understand the hydraulics of wetlands and how they affect treatment performance, researchers have worked on different approaches. Some have studied the effects of variation of hydraulic loading rate (HLR) defined as water inflow divided by wetland surface area (Wong & Geiger 1997; Werner & Kadlec 2000), geometry layout, subsurface berms, deep zones (Persson 2000, 2005; Lightbody *et al.* 2007) and vegetation (Kutija & Hong 1996; Jenkins & Greenway 2005). However, most of the studies addressing wetland hydraulics have been done in regard to wetlands in temperate regions, which may have its limitations considering water flow conditions and effects of vegetation, for example, as these differ with climatic region. It can be assumed that the treatment performance of tropical wetlands is different from that of temperate ones for many reasons, e.g. periods of extreme rain or drought, high evapotranspiration rates, year-round plant growth and microbiological activity, and higher macrophytic turnover rates (Kivaisi 2001; Abira 2007; Bojcevska 2007). Thus, when new wetlands have been designed in tropical regions, where most of the developing countries lie, their design has been based on already limited design models originally developed for temperate wetlands. Achieving optimal wastewater treatment and land utilization is at least as important in developing countries as elsewhere. Hence, a great need exists for data to calibrate and validate available design models for wetlands in the tropics (Konnerup *et al.* 2009).

Empirical evidence suggests that both macrophyte species and HLR can affect wetland treatment performance (Lin *et al.* 2002; Kyambadde *et al.* 2005; Bojcevska & Tonderski 2007). However, the mechanisms by which HLR and macrophyte species affect wetland hydraulics and hydrology are still not well understood. In fact, to the authors' knowledge there are few studies that have specifically investigated the hydraulic effects of HLR and macrophyte species in wetlands. Also, as most of the published studies have focused on comparing non-vegetated with vegetated wetlands or evaluated different layouts of vegetation, i.e. fringing or banded (Persson *et al.* 1999; Jenkins & Greenway 2005), questions remain concerning how different types of emergent macrophyte species influence the hydraulic regime of wetlands.

This paper aims to investigate how macrophyte species and HLR may affect hydraulic performance in small free water surface constructed wetlands (FWS CWs). The studied wetland system was part of a stabilization pond system located downstream of a sugar factory in western Kenya. A tracer experiment was used to assess the hydraulic effects of macrophyte species and HLR, respectively. Previous studies on the wetland system described in this study have confirmed significantly different area-specific mass removal rates of $NH_4^+$-N between the wetlands, with a higher removal rate in those planted with *Cyperus papyrus* than those planted with another macrophyte species (Bojcevska 2007; Bojcevska & Tonderski 2007). Also, former studies confirmed a significant positive linear relationship between area-specific mass removal of $NH_4^+$-N and mass loads (as a function of HLR) (Bojcevska 2007; Bojcevska & Tonderski 2007). Therefore, to further investigate the wetland system and possibly elucidate hydraulic differences between the wetlands, this study was undertaken.

The overall contribution of this study is to increase understanding of wetland hydraulics, which in the end may give support to wetland designers. As vegetation and HLR can typically be controlled in CWs, understanding how these parameters affect the hydraulic regime and performance will lead to better designed and managed wetlands.

## Study site – the Chemelil free water surface constructed wetland system

The study was performed near the Chemelil Sugar Company Ltd. in Nyanza Province, Kenya, at 1,269 m above sea level. The Chemelil Sugar Factory is considered to be among the top polluting industries near the Winam Gulf in Lake Victoria (Calamari *et al.* 1995). Wastewater from the sugar production characteristically contains high levels of nutrients, such as phosphorus (Bojcevska & Tonderski 2007). The factory effluent is treated in 12 serial ponds, each 100 m × 35 m in size. In December 2002, a pilot-scale FWS CW system was built close to the pond system. From pond

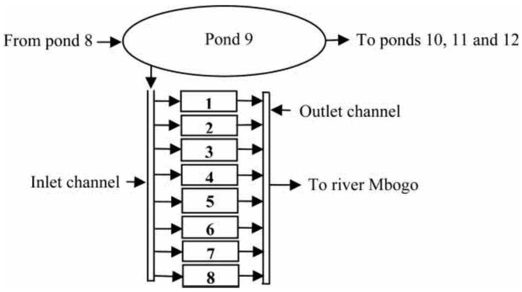


**Figure 1** | Schematic drawing of the Chemelil free water surface constructed wetland system. Constructed wetlands 1, 3, 5, and 7 were planted with *Cyperus papyrus* (C.p.) and 2, 4, 6, and 8 with *Echinochloa pyramidalis* (E.p.). Constructed wetlands nos. 1–4 received pre-treated sugar factory effluent in the amount of 45 (Low), whereas nos. 5–8 received 110 (High) mm day$^{-1}$ (drawing is not to scale).

9, some effluent was diverted to the wetland system through an open inlet channel (Figure 1).

Eight wetlands were dug out in the black cotton soil. Each wetland was approximately 3 m × 20 m. The wetlands were not lined with an impermeable material because it was assumed that the low permeability of the soil would largely prevent leakage of water flowing to and from the wetlands. However, a previous study of the present CW system revealed large problems with water leakages (Bojcevska & Tonderski 2007). Of the eight rectangular-shaped wetlands, four were planted with *C. papyrus* L. (nos. 1, 3, 5, and 7) and four with *Echinochloa pyramidalis* (Lam.) Hitche and Chase (nos. 2, 4, 6, and 8). In each wetland the inflow and outflow were centrally located at the widths. Constructed wetlands numbers 1–4 received pre-treated sugar factory effluent in the amount of 45 mm day$^{-1}$ (low), whereas numbers 5–8 received 110 mm day$^{-1}$ (high). After treatment in the wetland system, the water was discharged to the Mbogo River (Figure 1).

The macrophyte *C. papyrus* belongs to the sedge family Cyperaceae and grows in small patches, and has a thin and loose root mat that allows good water-plant interaction. It can be considered as an inflexible plant type due to its stiff stems. The diameter of the *C. papyrus* culms (stems) in this study were in the range of 0.75–5 cm. The macrophyte *E. pyramidalis* belongs to the grass family Poaceae, and grows with a compact root mat which may float on the water surface. The *E. pyramidalis* stems are more flexible than those of *C. papyrus*, and had a narrower diameter range (1.0–1.4 cm). At the time of the tracer experiment, the shoots of both macrophyte species were approximately 2 months old.

## Measures of wetland hydrodynamics – the hydraulic parameters

The hydraulic residence time (HRT) that most wetland researchers refer to is the nominal hydraulic residence time, which is defined as:

$$t_n = V/Q \tag{1}$$

where $t_n$ = nominal hydraulic residence time [h], $V$ = wetland water volume [m$^3$] and $Q$ = water flow rate [m$^3$ h$^{-1}$]. Thus, $t_n$ is representative of plug flow conditions where the entire wetland volume is in contact with flowing water. However, it is well known that these concepts do not apply to real wetlands. Instead, due to non-ideal conditions within the wetland each parcel of water will spend a different amount of time in the system, creating a residence time distribution (RTD) curve. For an impulse inert tracer introduced into a flowing wetland the RTD function is:

$$f(t) = \frac{QC(t)}{\int_0^\infty QC(t)\,dt} \tag{2}$$

where $f(t)$ = RTD function [h$^{-1}$]; $Q$ = water outflow rate [m$^3$ h$^{-1}$]; $C(t)$ = exit tracer concentration [g m$^{-3}$ = mg l$^{-1}$]; $t$ = time of sample [h] and d$t$ = change in time between samples [h]. The RTD function $f(t)$ quantitatively describes how much time different tracer particles have spent in the wetland. The numerator in Equation (2) is the mass flow of tracer in the wetland effluent at any time, $t$, after the impulse injection. The denominator is the sum of all the tracer recovered and should ideally equal the tracer mass added (Kadlec 1994).

From the RTD function, key parameters which describe the hydraulic properties of the wetland can be quantified. The first important parameter is the mean HRT of the wetland, defined in Equation (3):

$$t_{mean} = \int_0^\infty t f(t)\,dt \tag{3}$$

where $t_{mean}$ = mean hydraulic residence time [h]. Within this concept, the effective volume ratio of a wetland can be defined in Equation (4):

$$e = \frac{t_{mean}}{t_n} = \frac{V_{effective}}{V_{total}} \tag{4}$$

where $e$ = effective volume ratio; $V_{total}$ = total volume of the wetland [m$^3$] and $V_{effective}$ = total active wetland volume [m$^3$]. The second important hydraulic parameter that can be estimated from the RTD function is the variance which is defined in Equation (5):

$$\sigma^2 = \int_0^\infty (t - t_{mean})^2 f(t)\,dt \tag{5}$$

where $\sigma^2$ = variance of RTD [h$^2$]. The $\sigma^2$ value serves as an indicator of the spread of the RTD curve, where greater values of $\sigma^2$ mark greater spread of the RTD (Fogler 2006). At this point in the tracer data analysis, the internal water flow patterns for a wetland and their divergence from ideal flow conditions can be quantified, as follows.

The tanks-in-series model (TIS) has received much attention in treatment wetland science in the last decade due to its reasonably good capacity to describe non-ideal flow characteristics and thus pollutant reduction (Kadlec & Wallace 2009). In the TIS model the wetland is divided into a number of equally sized tanks ($N$), each of which is assumed to be a continuously stirred tank reactor (CSTR) (Levenspiel 1972; Kadlec & Wallace 2009). Special cases of the TIS model are the single CSTR ($N = 1$) and the plug flow reactor (PFR) ($N = \infty$). Thus, a high value of $N$ indicates a small degree of dispersion, short-circuiting and dead zones in a wetland, i.e. near-PFR conditions, while a low $N$-value defines the opposite. Reported $N$-values for FWS wetlands are in the range $0.3 < N < 10.7$ with a mean of $N = 4.1 \pm 0.4$ and appear to depend on wetland configuration (Kadlec & Wallace 2009).

According to Kadlec & Wallace, the $N$-factor for a wetland can be quantified as in Equation (6):

$$N = \frac{{t_{mean}}^2}{\sigma^2} \tag{6}$$

where $N$ = number of tanks in TIS model; ${t_{mean}}^2$ = squared mean hydraulic residence time [h$^2$] and $\sigma^2$ = variance of RTD [h$^2$]. The dimensionless nature of the $N$-factor makes it suitable both for comparing a wetland's divergence from ideal flow conditions and for comparison to other wetlands.

The two main factors $e$ (Equation (4)) and $N$ (Equation (6)) express two different hydrodynamic characteristics of a wetland. The first concerns how much of the total wetland volume is used, and the second describes the water flow patterns. In an attempt to synergise and weight these two factors equally, and also to enable a more comprehensive tool for evaluating and comparing hydraulic performance of wetlands, Persson *et al.* (1999) suggested the hydraulic efficiency factor defined in Equation (7):

$$\lambda = e\left(1 - \frac{1}{N}\right) = \frac{t_{peak}}{t_n} \tag{7}$$

where $\lambda$ = hydraulic efficiency [–] and $t_{peak}$ = maximum value of the RTD function [h]. The $\lambda$ factor combines $e$ (Equation (4)) and the 'flow pattern' parameter $N$ (Equation (6)) but the final expression is simply $t_{peak}$ divided by $t_n$. Thus, one main advantage of using $\lambda$ is that it can be determined directly from the peak value of the RTD function, thereby overcoming problems related to determination of $t_{mean}$ from tracer response curves, which is especially cumbersome with long residing tails (Persson *et al.* 1999).

## Hydraulic effects of wetland vegetation

Wetland vegetation dominates the drag resistance to water flow in FWS wetlands (Kadlec 1990; Kadlec & Wallace 2009). In fact, Kjellin *et al.* (2007) showed through both tracer test and computer simulations that vegetation in a treatment wetland in Sweden may dominate water flow patterns compared to bottom topography.

Wetland vegetation can affect water flow patterns and velocities on a large scale. Such effects are principally due to the distribution and density of vegetation stands, which may produce short-circuiting paths and dead zones (Persson *et al.* 1999; Jenkins & Greenway 2005). Thackston *et al.* (1987) stated that if vegetation formations give rise to dead zones, the result may be increased dispersion and decreased residence times for contaminants, thus lowering overall pollutant reduction efficiency. Wörman & Kronnäs (2005) showed, through a numerical model of a small wetland, that an increase of vegetation heterogeneity in fact did increase dispersion in a wetland system, which in turn reduced the pollutant removal. Further, Kjellin *et al.* (2007) found that vegetation heterogeneity was the only factor that could explain the multiple peaks in the RTD curve obtained from the tracer experiment. Also, increase in vegetation heterogeneity significantly contributed to spread of the RTD, where vegetation explained 60–80% of the variance in the observed RTD.

### Hydraulic effects of hydraulic loading rate

The HLR is one of the most essential features of treatment wetlands by significantly affecting their pollutant removal function (Lin *et al.* 2002; Bojcevska & Tonderski 2007; Kadlec & Wallace 2009). An increasing HLR may increase dispersion and thus also the distribution of oxygen, which can affect biological processes in a wetland. Also, high HLR caused by a flow event increases the water velocities, which may damage biofilms and thus affect the treatment performance of a wetland (Persson & Wittgren 2003). At lower HLR, on the other hand, convective circulation, caused by wind and sun, may dominate (Oldham & Sturman 2001; Borell Lövstedt 2008).

In a wetland, the depth-based Reynolds number (dimensionless) indicates the ratio of inertial to viscous forces on the water flow. The depth-based Reynolds number (Re) is defined as:

$$Re = \gamma \cdot d/v \qquad (8)$$

where $\gamma = |\gamma|$ absolute water velocity (m $h^{-1}$), $d$ = water depth (m) and $v$ = kinematic viscosity of water ($m^2$ $h^{-1}$). The Reynolds number determines whether turbulent or laminar flow is present in a wetland. The transition from laminar to turbulent flow is considered to occur at 2,000 to 2,300, i.e. Re < 2,000 being laminar flow and Re > 2,300 being turbulent. For CWs, typical Reynolds numbers are 1,000 or less (Kadlec & Wallace 2009).

## MATERIAL AND METHODS

### Hydrological measurements

The design inlet HLRs for the wetlands are displayed in Table 1. Manual water flow measurements were made daily during the period 13 January 2006 to 7 March 2006. All inlet pipes to the wetlands were fixed with gate valves that enabled manual adjustment of the flows. The inlet and outlet water flows from each wetland were measured every morning by use of a 2 L plastic container, a 1 L measuring cylinder, and a stop watch. At each wetland inlet, three measurements were made, and the HLRs were adjusted to the desired experimental HLR. Adjustment was done only if the measured inflow deviated more than ± 10% from the desired flow. For each CW, the daily inflows were represented by the mean value of the adjusted inflow and the measured inflow the following day. Each outflow was measured three times, and the mean was used to represent the outflow for the whole day.

**Table 1** | Wetland surface area, wetland volume, measured inlet HLR, measured outlet HLR, outlet HLR calculated from Equation (10) and water leakages calculated from Equation (11) (shown as % of $HLR_{in}$) for the seven free water surface constructed wetlands (CWs) at Chemelil Sugar Company Ltd. in Kenya. The HLR data represent mean values for the period 5–23 February for wetlands 2–4 and 5–15 February for wetlands 5–8. Wetlands were planted with *Cyperus papyrus* (C.p.) or *Echinochloa pyramidalis* (E.p.) and received pre-treated sugar factory effluent in the amount of around 45 (Low) or 110 (High) mm $day^{-1}$

| | CW 2 (E.p. Low) | CW 4 (E.p. Low) | CW 3 (C.p. Low) | CW 5 (C.p. High) | CW 7 (C.p. High) | CW 6 (E.p. High) | CW 8 (E.p. High) |
|---|---|---|---|---|---|---|---|
| Wetland surface area ($m^2$) | 54 | 53 | 60 | 62 | 54 | 58 | 54 |
| Wetland volume ($m^3$) | 18 | 21 | 18 | 20 | 18 | 29 | 20 |
| Measured $HLR_{in}$ (mm $day^{-1}$) | 43 | 40 | 43 | 110 | 108 | 110 | 102 |
| Measured $HLR_{out}$ (mm $day^{-1}$) | 33 | 24 | 19 | 88 | 97 | 97 | 89 |
| $HLR_{out}$ (mm $day^{-1}$) Equation (10) | 39 | 36 | 39 | 101 | 99 | 101 | 93 |
| % water leakages of $HLR_{in}$ | 13 | 31 | 47 | 12 | 1 | 4 | 5 |

Abbreviation: HLR = hydraulic loading rate.

Evapotranspiration (ET) can have a considerable impact on the water budget of a wetland system, especially in the tropics (Kyambadde *et al.* 2005; Abira 2007), and can also affect the mass balance calculations of wastewater pollutants entering and leaving the wetland (Bojcevska & Tonderski 2007). According to studies done on tropical CWs, wetland ET rates can range from 18–33 mm $day^{-1}$ (Lin *et al.* 2002), 7–17 mm $day^{-1}$ (Abira *et al.* 2003) and 9 mm $day^{-1}$ (Kadlec 2006). Also, Kadlec & Wallace (2009) pointed out that the use of the factor 0.8 to convert pan evaporation to potential evapotranspiration from wetlands can be invalidated due to short-term effects of vegetation during the growing season. Thus, in tropical wetlands where the growing season of the above-ground vegetation biomass takes place year-round (Kadlec & Wallace 2009) it could be justified to use a higher factor than 0.8. Also, because the tropical wetlands in the present study had small areas, high length to width ratios (7:1) and were located among dry sugar cane fields, the clothesline and oasis effect (Penman 1963; Linacre 1976) was probably substantial. In addition, Fermor *et al.* (2001) suggested that advection played a more important role for the energy budget in smaller wetlands located in dry areas, and that application of relatively high pan coefficients are justified in such sites. In conclusion, literature suggests that a higher pan coefficient than the recommended of 0.8 by Kadlec & Knight (1996) should be used to transform pan evaporation to wetland ET, especially for small wetlands located in dry tropical areas.

In this study, pan evaporation data were collected from a Class 'A' evaporation pan located only a few kilometres from the wetland site. Also, in order to quantify the ET rate of the present tropical CW system an empirical pan coefficient, $k$, of 1.4 [recommended by Peacock & Hess (2004) for reed beds in the UK], was used to convert pan evaporation $E_{PAN}$ to potential evapotranspiration $ET_o$ according to Equation (9). As the wetlands were wet 100 percent of the time, it was assumed that $ET = ET_o$ (Kadlec & Knight 1996):

$$ET = ET_o = kE_{PAN} \tag{9}$$

Using the coefficient of 1.4, a mean ET rate of 8.2 mm $day^{-1}$ for the study period was obtained, which is close to the ET rates reported by Abira *et al.* (2003) and Kadlec (2006). Precipitation data, P, were collected from the Meteorological Station near the Chemelil Sugar Factory. Due to significant variability in the outflows ($HLR_{out}$) from most wetlands, new values were calculated for this parameter according to Equation (10), using data for inflow ($HLR_{in}$), precipitation (P), and evapotranspiration (ET) (all in mm $day^{-1}$):

$$HLR_{out} = HLR_{in} + P - ET \tag{10}$$

For consistency new $HLR_{out}$ values were calculated for all wetlands.

## Other wetland features

Wetland areas were measured on 17 January 2006, and water depths on 2 February 2006. From these data the total volume for each wetland cell was calculated. Wetland vegetation density (stems $m^{-2}$) was measured on 8 February and 2 March 2006. To achieve this, three 1 $m^2$ areas in each wetland cell (one close to the inlet, one in the middle, and one close to the outlet) were selected. In each 1 $m^2$ area the total number of vegetation stems was counted. The vegetation density per $m^2$ of a wetland was taken as the mean of the stem counts from the three 1 $m^2$ areas of that wetland from the two measuring occasions. The total count of stems in each wetland was estimated by multiplying the mean stem counts per $m^2$ by the respective wetland area. In addition, the volumes of *C. papyrus* and *E. pyramidalis* stems in the wetland water were estimated on 2 March 2006. This was done by selecting three representative stems (small, medium and large) from wetland 1 and wetland 2, respectively. Each stem was submerged in a water-filled measuring cylinder to depth of 30 cm, in order to reflect the mean water depth in the wetlands. The difference in the volume of water in the measuring cylinder before and after submersion of a stem was noted and a mean volume for each vegetation species was calculated. The estimation of total vegetation volume was achieved by multiplying the mean vegetation volume for each species by the total count of stems in respective wetland.

The water volume in each wetland was taken as the difference between the total wetland volume and the vegetation volume. The nominal HRT ($t_n$) (Table 2) was

**Table 2** | Results of the hydraulic tracer study in the free water surface constructed wetland (CW) system, planted with *Cyperus papyrus* (C.p.) or *Echinochloa pyramidalis* (E.p.) and receiving pre-treated sugar factory effluent in the amount of 45 (low) or 110 mm day$^{-1}$ (high)

| | CW 2 (E.p. Low) | CW 4 (E.p. Low) | CW 3 (C.p. Low) | CW 5 (C.p. High) | CW 7 (C.p. High) | CW 6 (E.p. High) | CW 8 (E.p. High) |
|---|---|---|---|---|---|---|---|
| Mass tracer recovery (% of added) | 51 | 22 | 16 | 46 | 62 | 59 | 85 |
| $t_n$ (h) | 217 | 296 | 191 | 74 | 78 | 116 | 96 |
| $t_{mean}$ (h) | 129 | 255 | 179 | 55 | 68 | 119 | 65 |
| $t_{peak}$ (h) | 56 | 152 | 47 | 23 | 32 | 104 | 26 |
| $e$ (–) | 0.59 | 0.86 | 0.94 | 0.74 | 0.87 | 1.0 | 0.68 |
| $\lambda$ (–) | 0.26 | 0.51 | 0.25 | 0.31 | 0.41 | 0.89 | 0.27 |
| $N$ (–) | 1.6 | 3.4 | 1.9 | 1.5 | 1.9 | 3.2 | 1.9 |
| $NH_4^+$-N removal (g m$^{-2}$ day$^{-1}$) | 0.15 | 0.11 | 0.13 | 0.22 | 0.28 | 0.21 | 0.28 |
| Macrophyte density (stems/m$^2$) | 89 | 84 | 38 | 62 | 44 | 42 | 72 |
| % water of wetland volume | 99.4 | 99.5 | 97.5 | 96.2 | 97.4 | 99.8 | 99.5 |
| % macrophyte of wetland volume | 0.6 | 0.5 | 2.5 | 3.8 | 2.6 | 0.2 | 0.5 |

calculated as the water volume of a wetland divided by the mean measured water outflow of the wetland during the tracer study period.

## Water sampling and analyses

The tracer used in this study was lithium chloride (LiCl; 6% solution by mass). The tracer solution was prepared by mixing 200 g of LiCl (32.8 g Li) in 3.3 L of wastewater collected from the inlet pipe of each wetland. The pulse injection technique was used as it is commonly used and requires smaller amounts of tracer (Dierberg & DeBusk 2005). In order to avoid amounts of tracer elements settling at the bottom of the wetlands, the tracer was poured on a plate that distributed it well at the inlet point of the wetland.

The water sampling period was 5–23 February 2006 for wetlands 1 to 4, whereas wetlands 5 to 8 were sampled from 5–15 February 2006. Water samples were collected by placing a clean polyethylene bottle below the outlet pipe of each wetland. The samples were preserved with concentrated $HNO_3$ to pH < 2 *in situ*. Directly after the addition of the tracer, the first samples were collected from all wetlands. The next day after addition of the tracer, wetlands 1 to 4 were sampled in the morning at around 08:00 and late in the afternoon at 17:00 for 10 days, after which the sampling frequency was once a day for the next 8 days. For wetlands 5 to 8, samples were collected in the morning, (08:00), midday (12:00), and afternoon (17:00) for 5 days, after which the sampling frequency was once a day (12:00) for the next 5 days. Unfiltered $Li^+$ concentrations were analyzed with an atomic absorption spectrophotometer (Perkin Elmer model 1100) with an air-acetylene flame and at a wavelength of 670.8 nm (APHA, AWWA 1998). Standard solutions containing 0.01, 0.5, 1.0 and 2.0 mg $Li^+$ $L^{-1}$ were made to calibrate the spectrophotometer. Each sample was read five times and a mean value calculated.

In this study, the tail of the tracer concentration was extrapolated from at least five of the last data points by using an exponentially decreasing function, until 3 $t_n$ was reached.

Inlet and outlet water samples for $NH_4^+$-N were taken twice a week from 19 January 2006 to 7 March 2006. The samples were collected by putting a clean 500 mL plastic bottle below the inlet or outlet pipe of each CW. Outflows were sampled first, and inflow samples were taken before adjusting the inflows. The samples for were kept cool and analyzed within 3 h for $NH_4^+$-N with Lange cuvette tests designated LCK 304 and assessed in a DR. LANGE XION 500 spectrophotometer.

### Statistical analyses

Statistical analyses were performed using SPSS 17.0 for Windows. Kolmogorov–Smirnov and Levene's tests were used to examine the data for normal distribution and homogeneity of variance. To check for significant differences between the two experimental inlet HLRs, the Mann–Whitney test was employed. To test for significant differences between treatments on water leakages, mass tracer recovery, macrophyte density, % volume of macrophyte in the wetlands, two-way analysis of variance (ANOVA) analysis of variance was used. Also, significant differences in individual hydraulic parameters ($e$, $N$ and $\lambda$) as an effect of HLR and macrophyte species were determined by two-way ANOVA analysis of variance. To test for significant relationships between various parameters, a linear regression model was used. In the analysis of variance, the two HLRs and two plant species were separated by dummy variables. A value of $p < 0.05$ was chosen as the level of significance in all analysis cases.

## RESULTS

### Water balance

The mean operational inlet HLRs during the study period were very similar to the design HLRs of 45 and 110 mm day$^{-1}$ (Table 1). Also, it was statistically confirmed that the low operational inlet HLRs were significantly lower than the high operational inlet HLRs ($p < 0.001$) during the whole study period. Due to frequent events of no outflows from wetland 1, this wetland was excluded from the study.

This study confirmed results found by Bojcevska & Tonderski (2007) that the wetland system displayed some problems with water leakages (WL) calculated using the original data for outflow ($HLR_{out}$), inflow ($HLR_{in}$), precipitation (P), and evapotranspiration (ET) (all in mm day$^{-1}$) as:

$$WL = HLR_{in} + P - HLR_{out} - ET \quad (11)$$

Between 1 and 47% of the inlet HLR was lost due to water leakages. Most serious were the leakages in the low-load CWs, where 13–47% of $HLR_{in}$ was lost to the surrounding soil, whereas the high load CWs experienced only minor leakages (Table 1). However, neither an analysis of variance nor regression analysis showed a significant effect of macrophyte species or inlet HLR on water leakages (mm day$^{-1}$).

### Tracer recovery

The mass tracer recovery varied considerably between the wetlands, from 16% in wetland 3 to 85% in wetland 8 (Table 2). Still, no significant difference in tracer recovery (as % of added mass) as an effect of either macrophyte species or inlet HLR was detected. However, tracer recovery (as % of added mass) showed a significant negative linear relationship with water leakages (as % of $HLR_{in}$) ($R^2 = 0.68$; $p < 0.05$).

### Hydraulic parameters and RTD characteristics

Results displayed some unreasonably high values of $e$ and also a high variation of $\lambda$ (Table 2). The values of $N$ in this study ranged from 1.5 to 3.4. Generally, all of the RTD curves displayed long-tail forms typical for flowing wetlands with dispersion (Figure 2). Exceptions were the RTDs from CW 6 which displayed two peaks and CW 5 which displayed a peak after only one water sample was taken (Figure 2(b)). Further, the RTDs of CWs 2 and 3 were similar in shape (Figure 2(a)) and also these wetlands had similar $N$- and $\lambda$-values (Table 2). The RTD for CW 4 had a much higher $\lambda$-value than both CW 2 and 3 and the highest $N$-value of all wetlands. The RTDs for CW 7 and 8 were similar (Figure 2(b)) and these wetlands had the exact same $N$-value (Table 2).

### Effects of vegetation and hydraulic loading rate on wetland hydraulics

The wetland macrophyte densities varied between 38 and 89 stems m$^{-2}$. However, there was no significant effect of macrophyte species or HLR on macrophyte densities. Macrophytes occupied between 0.2 and 3.8% of the wetland volume whereas water occupied 96.2–99.8% (Table 2). In this context, the *E. pyramidalis* wetlands had significantly lower macrophyte volume compared with the *C. papyrus* wetlands ($p < 0.01$).

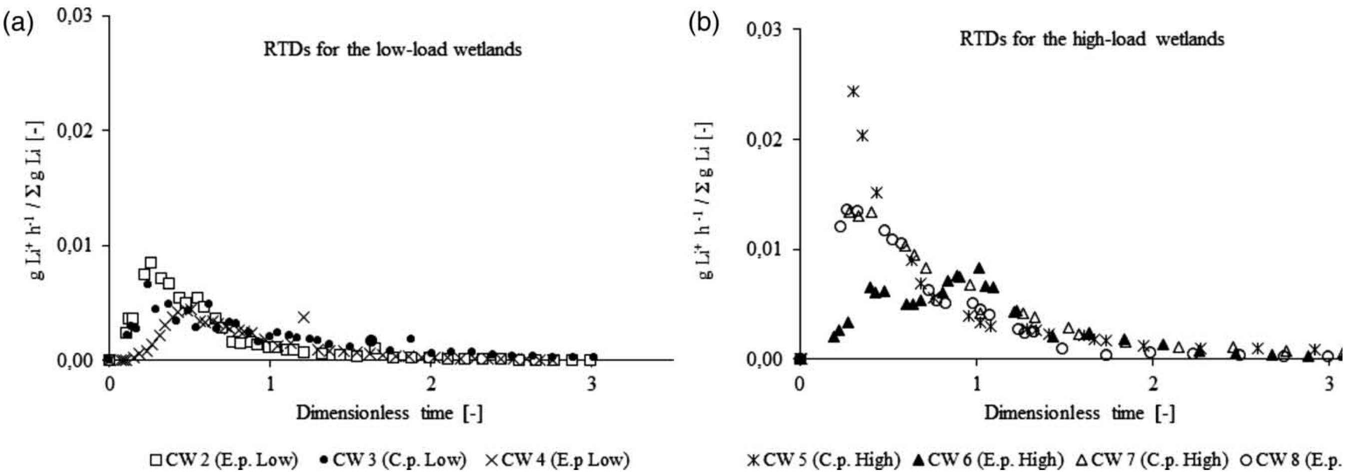


**Figure 2** | Residence time distribution curves for free water surface constructed wetlands dominated by *Cyperus papyrus* (C.p.) or *Echinochloa pyramidalis* (E.p.) and receiving pre-treated sugar factory effluent in the amount of 45 (a) or 110 (b) mm day$^{-1}$. The *x*-axis shows time normalized by the nominal residence time ($t_n$). The *y*-axis shows $Li^+$ mass at each time (g $Li^+$ $h^{-1}$) normalized by the total mass of recovered $Li^+$. Abbreviation: RTDs = Residence time distributions.

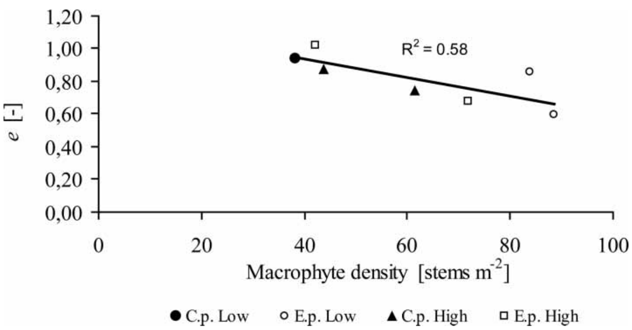


**Figure 3** | Relationship between effective volume ratio (*e*) and macrophyte density in the free water surface constructed wetland (CW) system at Chemelil Sugar Company Ltd. in Kenya, planted with *Cyperus papyrus* (C.p.) or *Echinochloa pyramidalis* (E.p.) and receiving pre-treated sugar factory effluent in the amount of 45 (Low) or 110 (High) mm day$^{-1}$ ($R^2 = 0.58$; $p < 0.05$).

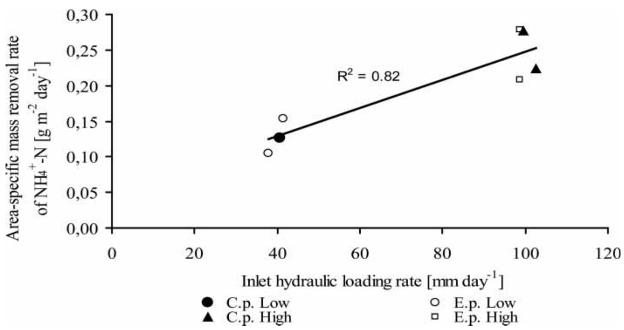


**Figure 4** | Relationship between area-specific mass removal rates of $NH_4^+$-N and inlet hydraulic loading rate in the free water surface constructed wetland (CW) system at Chemelil Sugar Company Ltd. in Kenya, planted with *Cyperus papyrus* (C.p.) or *Echinochloa pyramidalis* (E.p.) and receiving pre-treated sugar factory effluent in the amount of 45 (Low) or 110 (High) mm day$^{-1}$ ($R^2 = 0.82$; $p < 0.01$).

A significant negative linear relationship ($p < 0.05$) was found between $e$ and macrophyte density (stems $m^{-2}$), though the regression coefficient was relatively low (Figure 3; $R^2 = 0.58$).

There was no significant effect of either macrophyte species or HLR on $e$, $N$ and $\lambda$, respectively. Also, the depth-based Reynolds number, Re (Equation (8)) showed that laminar flow conditions prevailed in all wetlands (Re ~ 10–30).

## Effects of HLR on wetland treatment

No significant linear relationship between area-specific mass removal rates (g $m^{-2}$ day$^{-1}$) of $NH_4^+$-N and individual hydraulic parameters ($e$, $N$ and $\lambda$) was found (Table 2). However, two-way ANOVA showed that the high-load wetlands had significantly higher area-specific removal rates of $NH_4^+$-N compared with the low-load ones ($p < 0.05$), in fact almost twice as high. This effect was also confirmed by a significant positive linear relationship between area-specific removal rates of $NH_4^+$-N (g $m^{-2}$ day$^{-1}$) and inlet HLR data (Figure 4; $p < 0.01$; $R^2 = 0.82$). However, the interpretation of the result in Figure 4 should be taken with caution as the two HLRs resulted in fitting a line between two data clusters. Still, several studies have confirmed that higher HLRs, and thus normally higher mass loads of $NH_4^+$-N, have resulted in higher mass removal of $NH_4^+$-N ($g\,m^{-2}\,day^{-1}$) (Greenway & Woolley 1999; Lin *et al*. 2002; Bojcevska & Tonderski 2007).

## DISCUSSION

### Water balance and tracer recovery

The problems with water leakages in this wetland system have also been detected in a previous study (Bojcevska & Tonderski 2007). The implications of water leakages in a hydraulic tracer study are many, one of the most important being the effect on tracer recovery, which is further discussed in the next section.

The large variation in tracer recovery (Table 2) is indicative of some differences between the wetlands. Vegetation could represent a tracer sink by providing sorption sites (Dierberg & DeBusk 2005). In a study by Jenkins & Greenway (2005) it was indicated that the tracer recovery for vegetated wetland models was in fact generally less than that observed in non-vegetated ones. However, Abira (2007) reported both low and varied tracer recoveries (7–75%) in both unplanted and planted subsurface flow wetlands and also in planted FWS wetlands. Nevertheless, as there were no control wetlands the effect of the emergent macrophytes on tracer recovered cannot be evaluated in this study. Also, when considering macrophyte density in the wetlands, there was no significant connection with the amount of tracer recovered. Most likely, the macrophyte densities (Table 2) in the present study were not sufficiently different to allow for detection of possible differences in tracer recovery. For example, Jenkins & Greenway (2005) used a range of 10–1,000 stems $m^{-2}$ to test for significant effects on tracer recovery in wetlands.

Relative water leakage data in Table 1 were most likely a result of infiltration as the wetlands were not lined. As a result, a considerable amount of incoming water leaked out from the wetlands (especially from wetlands 3 through 6) to the surrounding areas. The significant negative linear relationship between tracer recovery and water leakages in the wetlands supports this argument ($R^2 = 0.68$; $p < 0.05$). Thus, this should indicate the importance of lining treatment wetlands in order to have better control of their water budget and thus more correctly assess their hydraulic performance and possible connections to treatment evaluation.

Despite the fact that this study was performed in the dry period, 78.9 mm of rainfall occurred, with 77% of this amount falling in one day. Consequently, this situation most likely had an impact on the hydrology of wetlands 1–4, which were still in sampling mode. More specifically, the heavy rain could have resulted in an increase of surface runoff, with a significant impact on the hydrological nature of the wetlands, and possibly also influenced the tracer recovery from these wetlands.

Also, short-circuiting paths in the wetlands could explain some of the low amount of tracer recovered. For example, the low tracer recovery (46%) in CW 5 (C.p. High) could be due to the fact that the measured tracer peak time occurred only 23 h after the addition of the tracer at the inlet (Table 2). This short tracer peak time could mean that some tracer in CW 5 was not measured and that the actual tracer peak time was not captured. Further, in the present study, the water flow measurements were done manually, which made it difficult to measure all of the flow variation in the wetland systems. This fact most likely contributed to some inaccuracy in calculations of tracer recoveries, $t_n$, $t_{mean}$ and related hydraulic parameters.

Schmid *et al*. (2004) and Kadlec & Wallace (2009) described density stratification problems of salt tracer as significant contributors to low tracer recoveries in wetlands. Kadlec & Wallace (2009) pointed out that 1% difference in density between the tracer solution and the wetland water was enough to uphold stratification that could critically affect hydraulic tracer experiments. In the present study the density difference was 3.2% and thus the risk of density stratification problems of the LiCl tracer could be considered as significant. Still, wetland 8 had an acceptable tracer recovery (Table 2). Thus, density stratification was most likely not a dominating factor for the low tracer recoveries in this study.

### Hydraulic parameters and RTD characteristics

Errors in measurements of wetland depths and areas could explain some of the unreasonably high values of $e$ and also the variant $\lambda$ values (Table 2). On the other hand, the observed $N$-values fall within the range of representative

*N*-values for FWS wetlands reported by Kadlec & Wallace (2009). Also, according to Kadlec & Knight (1996) *N*-values of 1–2 are not unusual in wetlands with open water areas due to wind induced mixing. Thus, considering the relatively low macrophyte densities and the observation of open water areas in both wetland types, the obtained *N*-values were not a surprise. The typical RTD shapes of both CW 5 (immediate peak time) and CW 6 (multiple peaks) were indicative of presence of both short-circuiting paths and dead zones (Figure 2(b)). Still, the *e* values for these wetlands indicated a high amount of effective volume, which is contradictory to the observed RTDs for these wetlands.

The observations of both high *e* and $\lambda$ for CW 6 were most likely related to underestimation of $t_n$ rather than an indication of high-quality hydraulic performance. Similarly, CW 4 had the highest *N* value and one of the highest *e* values of all wetlands, indicating good hydraulic performance. However, this wetland also displayed one of the highest water leakages (31%), which raised the question as to how effective this wetland actually was in both a hydraulic and a treatment perspective.

### Effects of vegetation on wetland hydraulics

Despite the domination of different macrophyte species and a significant difference in macrophyte volume between the species, no significant effect of macrophyte species on wetland hydraulics was found in this study. The low macrophyte volume (Table 2) most likely made detecting differences on a species level difficult. Thus, if the research objective is to investigate the effect of macrophyte species on wetland hydraulics, a situation with higher macrophyte volumes than the ones in this study might be more appropriate.

As would be expected from these results, the significant negative linear effect of macrophyte densities on *e* was independent of macrophyte species (Figure 3). Persson *et al.* (1999) and Jenkins & Greenway (2005) also found that vegetation had an effect on wetland hydraulics. More specifically, Persson *et al.* (1999) showed, using computer simulations that the *e* value increased from 0.38 to 0.68 when the wetland vegetation was changed from fringing to fully vegetated. The simulation results by Jenkins & Greenway (2005) indicated that increases in fringing vegetation density led to decreased hydraulic efficiency whereas increases in banded vegetation density had no such effect on wetlands hydraulics.

### Effects of HLR on wetland hydraulics and treatment

Results showed that HLR had no significant effect on *e*, *N* or $\lambda$. The most probable reason for this result was that laminar flow conditions dominated in the wetlands. Thus, detecting hydraulic differences due to HLR in the studied wetlands was difficult. Yet the HLRs used in this study were within a HLR range that is commonly used for FWS CWs (Kadlec & Wallace 2009). The use of turbulent water flow would not have been a realistic option for this wetland system.

A significant effect of HRL on area-specific mass removal rates of $NH_4^+$-N was observed (Figure 4). However, this result was not surprising as the effect of HRL on $NH_4^+$-N removal has been seen in a previous study (Bojcevska & Tonderski 2007). Still, it was somewhat surprising not to detect any connection between the removal rates and individual hydraulic parameters (*e*, *N* and $\lambda$). Most likely, other factors such as distribution of oxygen and bio film on the different wetland surfaces related to the HLR played an important role in the mass removal of $NH_4^+$-N, overriding the effect of hydraulics alone.

## CONCLUSIONS

For the Chemelil CW system, hydraulic tracer testing elucidated some hydraulic differences between the treatments. More specifically, this study demonstrated hydraulic effects of macrophytes and treatment effects of HLR in constructed treatment wetlands. The following conclusions can be made with support from the results:

1. Water leakages significantly affected the tracer mass tracer recoveries and thus most likely all other related hydraulic parameters. Thus, the significance of lining treatment wetlands for more accurate hydraulic evaluation and connections to treatment performance became apparent.

2. No significant effect of macrophyte species on wetland hydraulics was seen in this study. However, a significant negative linear effect of macrophyte density on wetland effective volume ratio was observed.
3. No hydraulic differences were observed between the wetland systems with regard to HLR. This was most likely because of the fact that the flow in the wetlands was laminar independently of HLR, and thus detecting hydraulic difference with regard to HLR was difficult. Nevertheless, the HLRs used in this study were within a 'realistic scope' and the use of turbulent flow would not have been a sensible option.
4. Mass removal rates of $NH_4^+$-N were observed to be significantly affected by HRL. However, no connection between the mass removal rates of $NH_4^+$-N and individual hydraulic parameters ($e$, $N$ and $\lambda$) was seen. Most likely other factors, such as distribution of bio film and oxygen, in interaction with the HLR also played an important role in the removal of $NH_4^+$-N, overshadowing the effect of hydraulics.

## ACKNOWLEDGEMENTS

This study was funded by the Research Department (SAREC) of the Swedish International Development Agency (Sida). Great appreciation is directed towards the Chemelil Sugar Company Ltd. in Kenya and the Agronomy Laboratory staff for enthusiastic support in the wetland research area. We are especially indebted to Mr B. Odhiambo Owour who helped out during the field measurements and sampling occasions. We also thank Lena Lundman for assistance during the water sample analyses. Finally, we thank Karin Tonderski as the initiator of the larger project that included the present study and Dr P. O. Raburu for being the local coordinator of the project.

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First received 11 March 2009; accepted in revised form 8 March 2011