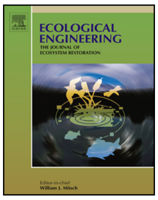
Ecological Engineering 67 (2014) 89–94

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng



The influence of evapotranspiration on vertical flow subsurface constructed wetland performance

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A R T I C L E I N F O

Article history:
Received 7 November 2013
Received in revised form 13 January 2014
Accepted 25 March 2014

Keywords:
Constructed wetlands
Evapotranspiration
Removal efficiency
Concentration
Mass balance
Water balance

A B S T R A C T

This paper presents an example of the importance of evapotranspiration in constructed wetlands, with vertical subsurface flow, comparing different methods of treatment efficiency calculations and discussing the influence of evapotranspiration on removal rates. The application of reed, marked by high transpiration ability, is a cheap and effective method of landfill leachate disposal. A 2-year study examined the effectiveness of leachate treatment in constructed wetlands with reed. Two kinds of vertical subsurface flow systems: first with sand, and second with combined two layers of sewage sludge and sand has been tested. 1, 3, and 5 mm d^{-1} hydraulic loading rates of landfill leachate have been applied. Daily evapotranspiration was in the range from 0.98 to 2.99 mm d^{-1} in the first year of research and from 2.56 to 4.61 mm d^{-1} in the second year. The influence of evapotranspiration rate on chemical oxygen demand (COD) removal rate was examined. Two methods of removal efficiency calculation have been used: first based on inlet and outlet COD concentrations, second on mass balance determination. Research showed that the removal efficiency calculated as a comparison between initial and final concentration is significantly lower, than expected from mass balance, especially, when higher hydraulic loading rates were applied.

1. Introduction

The use of ecological systems such as constructed wetlands (CWs), is recognized as an economical and technically sustainable solution for wastewater treatment making it safe to discharge into the environment. CWs are artificial complexes of water, matrix, vegetation and the associated invertebrate and microbial communities designed to simulate the ability of natural wetlands to remove pollutants from water (Brix, 1997), and are a good example of ecological engineering (Mitsch and Jorgensen, 2004). They provide an inexpensive and reliable method for treating a variety of wastewaters such as sewage, landfill leachate, mine leachate, urban storm-water, agricultural run-off, are very efficient for nutrient removal (Białowiec et al., 2011; Lu and Huang, 2010) are comparatively simple to construct, operate and maintain (Kadlec and Wallace, 2008; Randerson, 2006), and are suitable for advanced and polishing treatment if water reuse is an option (Marecos do Monte and Albuquerque, 2010; Masi and Martinuzzib, 2007; Pedrero et al., 2011).

Plants commonly used in constructed wetlands include: cattail (*Typha latifolia* L.), reed (*Phragmites australis* Trin ex Steudel), rush (*Juncus effusus* L.), yellow flag (*Iris pseudacorus* L.), mannagrass (*Glyceria maxima*), and giant reed (*Arundo donax* L.). As well as these typical natural wetland plant species, willow (*Salix* sp.), may be used in CWs with high efficiency (Aronsson and Perttu, 2001; Perttu and Kowalik, 1997).

Willows have been used in the treatment of agricultural runoff and leachate from landfill sites (Białowiec et al., 2007; Duggan, 2005), and are especially successful at removing high levels of ammonia and nitrogen from solution. Willow treatment systems also can achieve zero discharge of water due to evapotranspiration (ET), and part of the nutrients can be recycled via the plant biomass (Białowiec et al., 2011; Vymazal and Kropfelova, 2008). Some wetland species, such as reed, are tolerant of moderately high salinity

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http://dx.doi.org/10.1016/j.ecoleng.2014.03.032
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Table 1
The properties of landfill leachate used in the experiment (based on 48 samples).

Parameter	Unit	Mean	Standard deviation	Min. value	Max. value
Reaction	pH	8.0	0.4	7.2	9.13
COD	$mgO_2\,dm^{-3}$	1425.4	356.2	483.6	2467
BOD_5	$mgO_2\,dm^{-3}$	242.5	25.6[a]	148.4	368.3
Dissolved compounds	$mg\,dm^{-3}$	7164.1	806.9	5741	10,783
Loss on ignition	$mg\,dm^{-3}$	2672.6	748.7	1167	4110
	%	37.2	9.3	16.8	56.99
Residue after ignition	$mg\,dm^{-3}$	4491.6	802.4	3071	7872
	%	62.8	9.3	43.01	83.2
Electrolytic conductivity	$mS\,cm^{-1}$	12.3	1.1	9.74	14.21
Chlorides	$mgCl^{-}\,dm^{-3}$	176.3	19.4	124.95	227.5
Kjeldahl nitrogen	$mgN\,dm^{-3}$	779.3	95.2	551	992.8
Ammonia nitrogen	$mgN\text{-}NH_4^{+}\,dm^{-3}$	591.9	63.4	429.8	764.1
Phosphates	$mgP\text{-}PO_4^{-3}\,dm^{-3}$	3.6	1.3	0.08	5.5

[a] BOD_5/COD ratio = 0.17.

and provide high levels of nutrient removal, making them particularly suitable in treatment wetlands (Albuquerque et al., 2009; Białowiec et al., 2011; Lu and Huang, 2010; Mesquita et al., 2013).

To summarize, the presence of plants in a CW brings several benefits: plants may create aerobic conditions in an otherwise anaerobic rhizosphere, which induces growth of both heterotrophic and autotrophic aerobic bacteria; plants can provide carbon compounds into the rhizosphere that may be utilized by microorganisms in aerobic oxidation, fermentation and denitrification pathways; plants may uptake pollutants (N, P, heavy metals), from treated wastewater; plants may improve the hydraulic conditions of wastewater flow through the CW bed, and also may increase the available surface for microorganism biofilm growth.

Macrophytes have also a great potential for water loss through transpiration since they have inherently low water use efficiencies (Białowiec and Wojnowska-Baryla, 2007; Headley et al., 2012). Thus, water losses to the atmosphere via ET, can be high (Borin et al., 2011), especially under warm and windy conditions as observed in previous studies (Albuquerque et al., 2009; Białowiec et al., 2006). Numerous studies have shown the importance of ET during hot periods in both natural and CWs. ET may affect treatment efficiency of CWs because wastewater volume passing through the system decreases as a result of water loss. This phenomenon has been described widely in the literature. A decrease in volumetric flow through the wetland system and even a lack of effluent due to ET has been proven (Białowiec et al., 2006).

Usually, treatment efficiency of wastewater in CWs is calculated based on the concentration of pollutants (namely biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), nitrogen (TN) and total phosphorous (TP)) in inlet and outlet as in conventional treatment plants, without considering the contribution of evapotranspiration in the water balance. In a CW, where water loss is typically not negligible, the calculation of pollutant removal efficiency using results of concentrations may lead to significant errors. With ET, the concentration of dissolved compounds increases due to decreasing water volume, hence removal efficiencies calculated with and without the water balance are not the same, and this difference is assessed and discussed below.

This paper intends to show the importance of ET in CW performance calculations, using a vertical subsurface flow bed, comparing different methods of treatment efficiency calculations and discussing the influence of ET on removal rates.

2. Material and methods

2.1. System design and control

A municipal landfill in Wola Pawlowska near Ciechanów in Poland, operating since June 1994 (landfill area 3.5 ha), was the source of treated landfill leachate (LL), for this experiment, the properties of which are shown in Table 1. All parameters were determined according to standard methods (APHA-AWWA-WEF, 1999).

A laboratory scale experiment was conducted (Białowiec et al., 2007), using a 1 m high lysimeter (0.6 m in diameter and 0.28 m^3 in volume), as a model of a constructed wetland with vertical subsurface flow (VSSF). Each lysimeter (Fig. 1), contained a piezometer (5 cm diameter PCV tubing, closed at the top with a filter at the bottom), to enable bottom water sampling. A gravel layer (particle

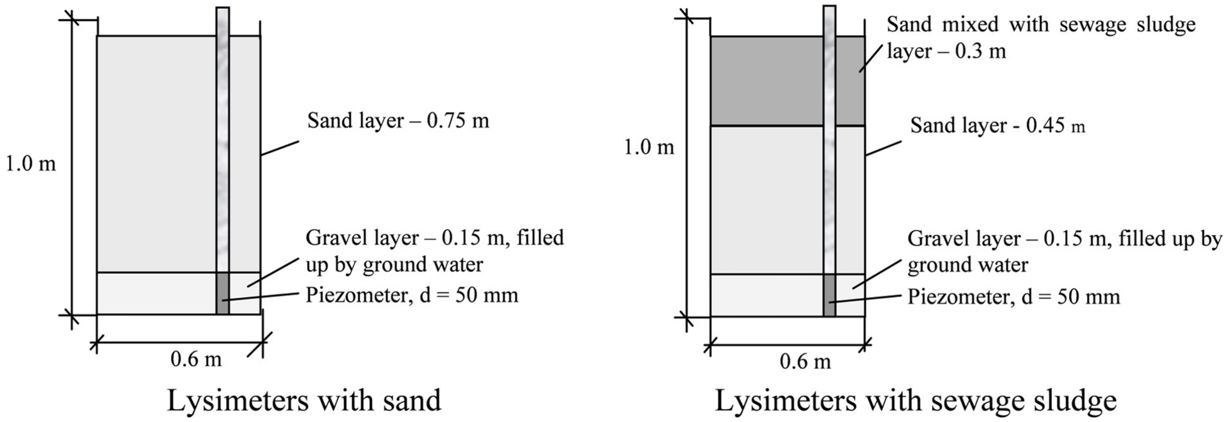

Fig. 1. Lysimeters construction.

Table 2
Physical and chemical characteristics of the soil used in the experiments (Białowiec et al., 2007).

Parameter	Unit	Soil type	
		Sand	Sand with sewage sludge
Reaction in 1 N KCl	pH	8.2	7.3
Organic matter	% d.m.	0.22	2.73
Kjeldahl nitrogen	% d.m.	0.003	0.22
Phosphorus	mg P_2O_5 100 g^{-1} soil	3.6	49.6
Salinity	g Cl^- dm^{-3} soil	0.1	0.8

diameter 10–20 mm) allowed drainage of percolating water. Above the gravel, fine sand was placed, as a filtering medium. In order to compensate the temperature inside the lysimeter and in the soil, the lysimeter was placed in the ground.

2.2. Experiment performance

The experiment was conducted during two vegetation seasons, as an example of VSSF with reed *Phragmites australis* (Cav.) Trin ex Steudel. ET and removal efficiency (RE) of organic compounds in VSSF was examined as a function of:

- Soil type: sand (S), and sand with a dose of 450 mg ha^{-1} as dry matter (d.m.) of sewage sludge (C);
- Leachate hydraulic loading rate (HLR): 1 mm d^{-1}, 3 mm d^{-1} and 5 mm d^{-1}. Each variant of the experiment was repeated three times.

The applied sewage sludge (pH 6.82; 57.8% moisture), contained 76.5% (of d.m.) organic matter and 1.21% (of d.m.) Kjeldahl nitrogen (Białowiec et al., 2007).

A 0.3 m deep layer of a sand-with-sewage-sludge mixture was settled at the top of the lysimeter. Sand soil and sand-with-sewage-sludge soil differed greatly in their physical and chemical properties. The content of the analyzed parameters in sand-with-sewage-sludge soil was about ten times higher than in sand soil, whereas sand soil pH was about 0.9 units higher than sand-with-sewage soil pH (Table 2). The content of organic matter in soil was measured again after 1st, and 2nd vegetation season (Table 3).

Into each lysimeter 7 reed-stocks were planted at a depth of 10 cm.

The lysimeters were located under a foil roof, which had been firmly insulated. There was no natural rainfall or natural groundwater inflow into the lysimeters. All the lysimeters were watered (Q_{inf}) in the following ways: with landfill leachate (Q_l) according to the prescribed HLR (once per week); by simulation of rainfall (Q_p) – distilled water, according to meteorological data (once per week); and incoming clean ground water (Q_s) – distilled water (once per month). Watering was performed by pouring out weighed amounts of water and leachate into the lysimeters. The reason for using distilled water was to exclude the influence of rain and ground water based contamination on pollutant mass balance. Once per month free drainage water (Q_{eff}) that had gathered inside the lysimeter was pumped out through the gravel layer and the piezometer using a peristaltic pump, prior to weighing. All types of liquids being a part of each lysimeter's water balance: Q_l, Q_p, Q_s, and Q_{eff} were weighted (kg), and then converted into (mm d^{-1}) units, according to appropriate time intervals.

2.3. Treatment efficiency

Evapotranspiration (ET) was estimated according to Eq. (1), considering Q_{inf} as the total amount of water added to the lysimeter (mm d^{-1}), and Q_{eff} as the amount of water pumped out from the lysimeter (mm d^{-1}). Q_{inf} was computed using Eq. (2).

$$\mathrm{ET} = Q_{inf} - Q_{eff} \tag{1}$$

$$Q_{inf} = Q_l + Q_p + Q_s \tag{2}$$

where Q_l is the amount of added landfill leachate (mm d^{-1}), Q_p is the amount of precipitation (mm d^{-1}), and Q_s is the amount of added ground water (mm d^{-1}).

Removal efficiency (RE) of COD in the VSSF was calculated, based on concentrations (Eq. (3)) and based on loads (Eq. (4)).

$$\mathrm{RE} = \frac{C_{inf} - C_{eff}}{C_{inf}} \cdot 100\% \tag{3}$$

where C_{inf} and C_{eff} are the mean concentrations (mg L^{-1}) of a compound in the influent and the effluent, respectively.

$$\mathrm{RE} = \frac{(C_{inf} \cdot Q_{inf}) - (C_{eff} \cdot Q_{eff})}{(C_{inf} \cdot Q_{inf})} \cdot 100\% \tag{4}$$

where $C_{inf} \cdot Q_{inf} = M_{inf}$ (mg) and $C_{eff} \cdot Q_{eff} = M_{eff}$ (mg), are inflow and outflow mass load, respectively.

The two measures of removal efficiency were compared and correlations between ET and COD removal efficiencies were determined.

3. Results and discussion

The experiment showed that ET depended on both HLR and soil type. The daily ET differed between successive vegetation seasons. In the first year after planting, during the young reed plants' development ET values were lower than in the second vegetation season, when plants were well grown (Table 4).

It can be observed that ET from systems containing sand with sewage sludge mixture was higher than that from the systems with sand alone, throughout the two years of the experiment. The addition of organic material (sewage sludge) seems to improve the growth conditions for reed, resulting in higher transpiration rates. Also, ET increased with the rise of HLR during two vegetation seasons in both kinds of soil. The highest value of daily ET, 4.61 mm d^{-1}, was obtained in the second year in VSSF covered by sand with sewage sludge mixture, with HLR 5 mm d^{-1} of landfill leachate.

Table 3
Content of organic matter in soils during the experiment.

Time of soil sampling	Soil type					
	Sand			Sand + sludge		
	HLR 1 mm d^{-1}	HLR 3 mm d^{-1}	HLR 5 mm d^{-1}	HLR 1 mm d^{-1}	HLR 3 mm d^{-1}	HLR 5 mm d^{-1}
Start of the experiment	0.22	0.22	0.22	2.73	2.73	2.73
After 1st vegetation season	0.2	0.33	0.26	2.68	2.87	2.45
After 2nd vegetation season	0.2	0.29	0.2	4.82	4.59	4.24

Table 4
Performance of reed VSSF on COD removal for landfill leachate treatment depending on the soil type, and hydraulic loading rate in successive vegetation seasons.

Vegetation season	Parameters	Soil type					
		Sand			Sand + sludge		
		HLR 1 mm d^{-1}	HLR 3 mm d^{-1}	HLR 5 mm d^{-1}	HLR 1 mm d^{-1}	HLR 3 mm d^{-1}	HLR 5 mm d^{-1}
1st vegetation season	COD$_{inf}$ (mg L^{-1})	1266.4 SD ± 242.9					
	COD$_{eff}$ (mg L^{-1})	124.5 SD ± 35.5	359.1 SD ± 114.5	569.2 SD ± 196.2	96.7 SD ± 33.0	316.9 SD ± 107.0	576.7 SD ± 201.9
	M(COD)$_{inf}$ (mg)	10.3 SD ± 2.1	30.8 SD ± 6.4	49.0 SD ± 15.3	10.3 SD ± 2.1	30.8 SD ± 6.4	41.0 SD ± 13.5
	M(COD)$_{eff}$ (mg)	2.3 SD ± 0.6	11.9 SD ± 2.6	24.5 SD ± 8.5	1.2 SD ± 0.5	7.6 SD ± 3.6	12.5 SD ± 6.2
	Concentration RE for COD (%)	90.2 SD ± 2.0	72.1 SD ± 3.7	56.2 SD ± 7.7	92.5 SD ± 2.1	75.3 SD ± 7.1	53.6 SD ± 15.4
	Mass load RE for COD (%)	77.88 SD ± 2.76	61.6 SD ± 1.5	50.1 SD ± 4.2	88.3 SD ± 4.1	75.6 SD ± 11.0	68.6 SD ± 13.6
	ET (mm d^{-1})	0.98 SD ± 0.61	1.00 SD ± 0.46	1.48 SD ± 0.48	1.59 SD ± 0.66	2.22 SD ± 1.07	2.99 SD ± 0.89
2nd vegetation season	COD$_{inf}$ (mg L^{-1})	1537.8 SD ± 249.8					
	COD$_{eff}$ (mg L^{-1})	252.9 SD ± 277.7	285.6 SD ± 96.2	710.4 SD ± 343.9	310.0 SD ± 385.0	860.2 SD ± 937.6	1145.8 SD ± 1000.8
	M(COD)$_{inf}$ (mg)	13.3 SD ± 3.6	38.5 SD ± 10.3	53.4 SD ± 13.5	13.3 SD ± 3.6	39.8 SD ± 10.8	62.0 SD ± 17.9
	M(COD)$_{eff}$ (mg)	2.2 SD ± 0.7	7.4 SD ± 1.0	21.3 SD ± 4.2	1.2 SD ± 0.2	4.6 SD ± 1.1	18.8 SD ± 7.1
	Concentration RE for COD (%)	83.3 SD ± 18.5	80.9 SD ± 6.8	53.8 SD ± 16.8	79.5 SD ± 25.6	46.9 SD ± 53.9	28.0 SD ± 56.1
	Mass load RE for COD (%)	82.3 SD ± 5.5	79.3 SD ± 8.2	59.7 SD ± 5.1	89.1 SD ± 2.3	86.8 SD ± 8.2	69.4 SD ± 9.9
	ET (mm d^{-1})	2.72 SD ± 1.47	2.56 SD ± 1.22	2.69 SD ± 1.17	3.51 SD ± 1.89	3.95 SD ± 2.42	4.61 SD ± 2.33

SD: standard deviation.

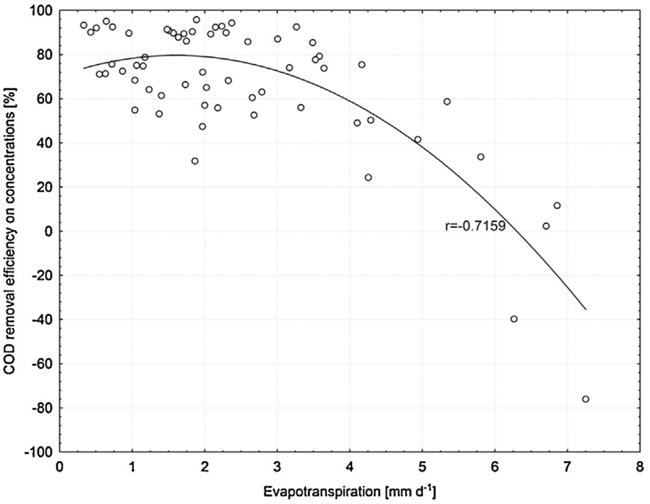

Fig. 2. Correlation between ET and COD removal efficiency calculated using concentrations for the VSSF.

The experiment showed that ET influenced the RE of organic compounds. The average values of organic compounds, expressed as COD concentrations in the influent and effluent, as well as the corresponding mass loads introduced to, and eluted from, the systems are shown in Table 4, together with calculated RE average values. It is evident that treatment efficiency, calculated on the basis of both concentrations and loads, decreased with the increase of HLR, in all variants.

Treatment efficiency presents different values if calculated based on concentrations or based on mass loads. In systems with sand there was little difference between removal efficiencies calculated using either concentrations or loads, during both vegetation seasons, but the higher values were observed for concentrations. Plant growth and hence ET were low, ranging from 0.98 to 2.72 mm d^{-1} (Table 4), due to the poor nutritional conditions of sand soil (the content of nutrients such as N, and P, was very low in sand, about 10 fold lower than the in mixture of sand-with-sewage-sludge; additionally, the proportion between N and P in landfill leachate was unbalanced, which could cause high deficiency of P). Under these conditions, water losses were too small to influence pollutant removal efficiency.

In systems with soil mixture containing sand-with-sewage sludge, especially during the second vegetation season, and at higher HLR, ET caused a marked reduction in removal efficiency based on concentrations compared to that based on mass loads. The highest difference was observed in the system with HLR 5 mm d^{-1} during the second year where the highest ET was found (4.61 mm d^{-1}). Average RE based on concentration was only 28%, whereas the value based on loads reached 69% (Table 4).

Moreover in two cases the concentration of COD in the effluent was higher than in the influent, resulting in negative values of treatment efficiency (Fig. 2). There is a strong correlation overall between ET and COD removal efficiency based on concentration (Fig. 2), but when ET is low (below 2.5 mm d^{-1}), removal efficiency does not depend on ET. As ET starts to rise above 2.5 mm d^{-1} water losses cause an increase in the pollutant concentration in the effluent, resulting in a rapid decrease of apparent removal efficiency. At higher values of ET, final concentrations may be even higher than initial (Fig. 2).

In contrast, there was no significant dependence of ET on COD removal efficiency calculated using mass loads. An irregular scatter of COD removal efficiency values across the whole range of ET was found (Fig. 3).

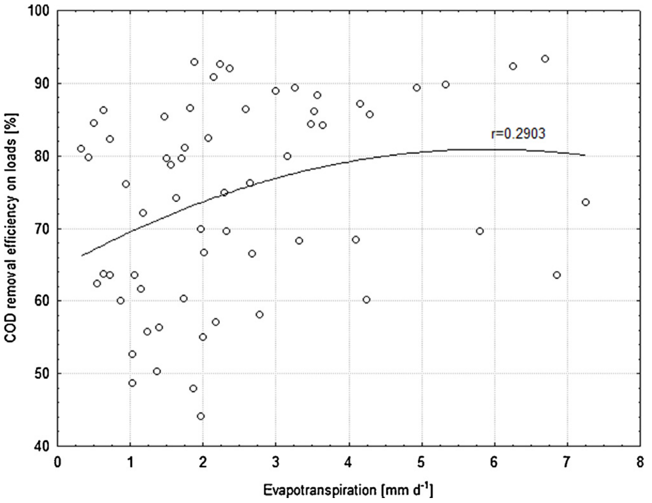

Fig. 3. Correlation between ET and COD removal efficiency calculated using mass loads for the VSSF.

These results indicate the need for calculations of pollutant removal efficiency to be based on loads rather than on concentrations, for the evaluation of CW treatment performance.

Additionally, the influence of ET on organic matter accumulation in soil was found, but only during 2nd vegetation season, when the content of organic matter doubled in systems with mixture of sand-with-sewage-sludge (Table 3). It confirms, that plants, under good growing conditions, affect the organic removal efficiency not only by supporting the microbial community (Brix, 1997), but also by increasing the accumulation in media due to the high rate of transpiration. High accumulation of organic matter observed in 2nd vegetation season, could also influence the low values of RE based on concentrations, possibly due to rinsing of organic matter out of the bed. This effect may have resulted in increased concentration of organic matter in wastewater effluent.

Small-scale wetland areas such as CWs, frequently show enhanced ET (the so-called “clothesline” and “oasis” effects), due to a strong influence of advection from the relatively warm, dry air of the surrounding terrestrial microclimate (Borin et al., 2011; Kadlec and Wallace, 2008). High rates of water loss from treatment wetlands in central Europe, planted with reed, are quoted by Siuta (1996), (1000) to 1400 mm y^{-1}, Wieuner et al. (1999), approximately 1500 mm y^{-1}, and for sludge drying reed beds in Denmark by Nielsen (1993), approximately 1500 mm y^{-1}. Borin et al. (2011), found ET for reed bed CWs in Italy to be 6–7 times higher than that for a reference crop (based on Penman calculations), when averaged over the growing season.

A particularly important aspect of landfill leachate disposal in CWs is the reduced leachate volume due to ET by planted macrophytes, typically willows, poplars and reeds (Białowiec et al., 2007), during periods when rainfall input is relatively low. In a study of ET in reed CWs beds treating landfill leachate, Surface et al. (1993), found the greatest decrease in leachate volume (43%), occurred between May and July in the second year of growth when stem biomass was greater, whereas volume reduction of only 21% occurred in the winter period (from October to April). Agopsowicz (1994), determined that ET by young (3-month), willow sprouts supplied with landfill leachate was 1.6–1.8 times higher than the average precipitation rate in Poland, (about 600 mm). In a 2-year study of a soil-plant system with young willow sprouts (*Salix amygdalina* L.), Białowiec et al. (2007), found ET values of 2–3 mm d^{-1}, which were up to 5 times higher than for a bare soil surface, and resulted in volume reduction between 80 and 90%. Similar ET values were found for reeds in soil-plant systems, at 1–3 mm d^{-1} in the 1st year of growth and 3–5 mm d^{-1} in the 2nd year, reflecting an increase in reed stem biomass (Białowiec and Wojnowska-Baryla, 2007).

Moreover, where the vegetated CWs area is sufficiently large, there may be no effluent discharge, at least during summer months, for example in a wastewater treatment reed bed in Poland (Białowiec and Randerson, 2010). In a marsh-pond-meadow system with recirculation, implemented for municipal wastewater treatment in Kentucky (Choate et al., 1993), as a result of ET and seepage no outflow occurred over 4 years except following one heavy rain event. In sensitive locations where stringent conditions for effluent quality prevent discharge to environment as in Denmark, zero-discharge wetland systems using willows to reduce effluent volume have been employed (Gregersen and Brix, 2001). Conversely, in areas of low rainfall, the aim may be to minimize ET losses in a CW, as treated effluent may be required to be re-used (El Hamouri et al., 2007; Green et al., 2006; Headley et al., 2012; Masi and Martinuzzib, 2007).

Regarding the operating conditions, most of the studies with VSSF (Cheng et al., 2011; Vymazal, 2007) evaluate the treatment efficiency of beds based on concentrations (C_{inf} and C_{eff}) as presented in Eq. (3).

The experiment presented in this work shows higher values of RE calculated using mass loads in VSSF than using concentrations, especially for high values of HLR (Table 4), as also found by Finlayson and Chick (1983), who calculated the RE for COD, TSS, TKN and TP, taking into account the influent and effluent concentrations (Eq. (3)) and the influent and effluent mass loads as in Eq. (4). Percentage removal rates calculated for mass loads were higher than those for concentrations, because Eq. (4) is more sensitive to flow rate fluctuations caused by variation in ET.

This approach relates to specific conditions within a CW bed, where the influence of plants is not only on pollutants, but also on water. Plants transpire water into the atmosphere, causing an increase in concentration of pollutants in water and soil. Simultaneously, microbial degradation is in progress and is dependent on oxygen concentration, HLR, influent loads and temperature, among other factors. Therefore, two independent processes seem to have occurred: reducing the molecules of both pollutants and water. Depending on the relative rate of each process, the final pollutant removal efficiency value differs. When ET is low, the difference between RE calculated through Eq. (3) or Eq. (4) is small. As ET rises, so the RE based on mass loads increases relative to that based on concentrations.

Therefore, the RE calculated through mass loads of compounds (given by Eq. (4)) seems a more accurate method for performance evaluation in wetland systems than the method based only on influent and effluent concentrations.

4. Conclusions

In a constructed wetland (CW) plants contribute to pollutant removal and nutrient uptake from wastewater, improve the hydraulic flow through beds, and also have great transpiration potential. Evapotranspiration affects treatment efficiency in CWs increasing the concentration of dissolved compounds due to decreasing of water volume, and increasing the accumulation of pollutants in soil. Data from experiments with a VSSW and landfill leachate shows that the removal efficiency calculated as a comparison between initial and final concentration is lower, than expected from mass balance. Usually, removal efficiency is expressed on the basis of concentrations, mostly due to lack of flow rate monitoring. Unfortunately, this may seriously underestimate treatment performance of CWs, especially when evapotranspiration rate exceeds 2.5 mm d^{-1}. That situation may occur when nutrient-rich media are applied. This study suggests the need for routine monitoring of flow rate, or evaluation of potential evapotranspiration, to estimate removal efficiency of a CW based on mass balance.

Acknowledgement

This research work was supported by the Wroclaw University of Environmental and Life Sciences (Wroclaw, Poland), University of Beira Interior (Covilha, Portugal) and Cardiff University (Cardiff, UK).

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