WATER RESEARCH 47 (2013) 769–780

Available online at www.sciencedirect.com

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Performance evaluation of different horizontal subsurface flow wetland types by characterization of flow behavior, mass removal and depth-dependent contaminant load

Eva M. Seeger[a,*], *Uli Maier*[b], *Peter Grathwohl*[b], *Peter Kuschk*[a], *Matthias Kaestner*[a]

[a] *Department of Environmental Biotechnology, Helmholtz Centre for Environmental Research – UFZ, Permoserstr. 15, 04318 Leipzig, Germany*
[b] *Center of Applied Geoscience, University of Tübingen, Hölderlinstr. 12, 72074 Tübingen, Germany*

ARTICLE INFO

Article history:
Received 10 March 2012
Received in revised form
30 October 2012
Accepted 31 October 2012
Available online 15 November 2012

Keywords:
Tracer test
Fluorescein
Hydroponic plant root mat
Local contaminant loads
Benzene
MTBE
Ammonium removal

ABSTRACT

For several pilot-scale constructed wetlands (CWs: a planted and unplanted gravel filter) and a hydroponic plant root mat (operating at two water levels), used for treating groundwater contaminated with BTEX, the fuel additive MTBE and ammonium, the hydrodynamic behavior was evaluated by means of temporal moment analysis of outlet tracer breakthrough curves (BTCs): hydraulic indices were related to contaminant mass removal. Detailed investigation of flow within the model gravel CWs allowed estimation of local flow rates and contaminant loads within the CWs. Best hydraulics were observed for the planted gravel filter (number of continuously stirred tank reactors $N = 11.3$, dispersion number = 0.04, Péclet number = 23). The hydroponic plant root mat revealed lower N and pronounced dispersion tendencies, whereby an elevated water table considerably impaired flow characteristics and treatment efficiencies. Highest mass removals were achieved by the plant root mat at low level: 98% (544 mg m^{-2} d^{-1}), 78% (54 mg m^{-2} d^{-1}) and 74% (893 mg m^{-2} d^{-1}) for benzene, MTBE and ammonium–nitrogen, respectively. Within the CWs the flow behavior was depth-dependent, with the planting and the position of the outlet tube being key factors resulting in elevated flow rate and contaminant flux immediately below the densely rooted porous media zone in the planted CW, and fast bottom flow in the unplanted reference.

1. Introduction

Constructed wetlands (CWs) have proven to be an efficient ecological technology for the treatment of various kinds of contaminated waters (Williams, 2002; Haberl et al., 2003; Kadlec and Wallace, 2008), including domestic and agricultural wastewater (Konnerup et al., 2009; Vymazal and Kröpfelová, 2009), landfill leachate (Bulc, 2006; Yalcuk and Ugurlu, 2009), industrial effluents (Vymazal, 2009) and groundwater contaminated with organic chemicals (Braeckevelt et al., 2008; Seeger et al., 2011a). The use of CWs has been successfully tested in pilot- (Braeckevelt et al., 2011) and field-scale (Ferro et al., 2002; Moore et al., 2002) applications, providing data on overall contaminant removal efficiency on the basis of either concentrations or loads.

CW treatment efficiency primarily depends on the contact time between the contaminated water and the filter material, including biota, as longer residence times enhance

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* *Corresponding author*. Tel.: +49 341 2351765; fax: +49 341 2351471.
E-mail address: eva.seeger@ufz.de (E.M. Seeger).

0043-1354/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.watres.2012.10.051

contaminant turnover (Werner and Kadlec, 1996). Hence, the characterization of hydraulic flow in CWs is crucial for the evaluation and optimization of system designs and performances (Persson et al., 1999). Moreover, detailed knowledge on flow behavior is essential for the validation and improvement of existing models. The hydraulic characterization of CWs is mostly based on tracer experiments, where the analysis of outlet breakthrough curves (BTCs) using the temporal moment method allows the calculation of the CWs' flow characteristic parameters, such as the mean residence time (τ), porosity (θ), variance (σ^2), and dispersion parameters. These system-specific parameters may reveal whether the CW is actually operating with ideal flow, short-circuiting, or dead zones, and allow for a comparison between differently designed and operated CWs (Werner and Kadlec, 1996; García et al., 2004; Holland et al., 2004). Since the connection between hydraulic residence time and treatment efficiency has been recognized, many studies have already evaluated the effects of wetland design parameters (e.g. aspect ratio, inlet/outlet configuration, filter medium size, or plant development) and operational modes on the flow behavior or the removal efficiency (García et al., 2005; Kjellin et al., 2007; Ascuntar Ríos et al., 2009; Su et al., 2009; Hijosa-Valsero et al., 2010). Nevertheless, investigations that simultaneously encompass the hydraulic characterization of different CW systems, the change of hydraulic parameters due to operational mode adaptation, and the respective contaminant removal efficiency are rare (Ascuntar Ríos et al., 2009). Most studies evaluate treatment efficiency based on the black box concept, only focusing on overall removal rates. Some studies additionally provide contaminant concentrations of the pore water. However, loads within the wetland have not been described previously, given that actual flow at the sampling points was unknown.

Therefore, the goal of our work was to evaluate the flow characteristics of various pilot-scale horizontal subsurface flow CWs (two conventional wetlands with a gravel filter (planted and unplanted) and a plant root mat system without gravel matrix) and to relate the hydraulic parameters obtained from tracer tests to the achieved treatment efficiencies. For the plant root mat, the effect of low and high water level on both the hydraulic parameters and the pollutant removal was also investigated. Furthermore, local flow rates and local contaminant loads were assessed for the gravel-based CWs in order to identify preferential flow paths and zones with enhanced contaminant flux. The analysis is based upon local tracer BTCs monitored at various sampling points in the porous media.

2. Material and methods

2.1. *Constructed wetland design*

The study was carried out at the so-called CoTra (Compartment Transfer) research site in Leuna, Germany, where six pilot-scale horizontal subsurface flow (HSSF) CWs were set up during 2007 in order to evaluate the optimized CW design for the remediation of the local groundwater, which is contaminated with benzene (~20 mg L^{-1}), methyl *tert*-butyl ether (MTBE) (~3.7 mg L^{-1}) and ammonium (57 mg L^{-1}) (Seeger et al., 2011a,b). All CWs consisted of steel basins (5 m length × 1.1 m width × 0.6 m height). Totally, three CWs were studied. CW A and B were filled with gravel (grain size 2–3.2 mm) to a height of 50 cm, with the water level set to 40 cm. System A was planted with common reed (*Phragmites australis*); system B remained unplanted as a reference. Each wetland was designed with in- and exfiltration zones (0.4 m × 1.1 m × 0.6 m) adjacent to the in- and outflow, containing coarse gravel (quartz, grain size 3–8 mm) in order to ensure an even distribution of the inlet stream over the entire wetland cross-section and prevent clogging of the outflow tubes. System C was constructed as a hydroponic plant root mat (*P. australis*), without a gravel matrix except for the in- and exfiltration zone, and was operated at 15 cm (April 2008–September 2009) and 30 cm (since October 2009) water levels. The hydroponic root mat rested on the bottom of the basin at low water level and floated at elevated water level. The groundwater inflow was supplied from a nearby groundwater well; detailed characteristics are provided in Seeger et al. (2011a). Inflow and outflow connections were installed 5 cm above the bottom of the basins; in- and outflow volumes were regulated by pumps. During the time of the tracer test, the hydraulic loading rate was 12 L h^{-1} for systems A and B, and 6.9 L h^{-1} for system C independent on its water level. At these loading rates the theoretical residence times are similar for CW A, B and C (at low water level) (see Table 1). This is a prerequisite for comparing the treatment efficiency of the CW systems. Inflow and outflow volumes were quantified by flow meters every 15 min, allowing accurate determination of tracer and contaminant loading rates.

Table 1 – Overview of operational characteristics of the constructed wetland systems (estimated pore volume (V_{sys}), mean inflow rate (Q_{in}), mean flux (Q_{mean}), theoretical hydraulic retention time (*n*HRT)) and experimental settings for the tracer studies conducted (fluorescein concentration of the tracer solution (c_{tracer}), time interval of tracer injection (Δt), total mass of tracer applied (M_{in})). For the gravel CWs, V_{sys} was calculated using a mean gravel porosity ($n = 0.35$). For the hydroponic plant root mat system, V_{sys} was derived by means of wetland draining and refilling.

	Gravel filter		Hydroponic plant root mat	
	Planted	Unplanted	Low water level (15 cm)	High water level (30 cm)
V_{sys} [L]	770	770	422	1041
Q_{in} [L d^{-1}]	287	288	167	166
Q_{mean} [L d^{-1}] = (Q_{in} + Q_{out})/2	254	274	136	155
*n*HRT [d] = V_{sys}/Q_{mean}	3.05	2.81	3.11	6.72
c_{tracer} [mg L^{-1}]	112	112	153	136
Δt [h]	4.12	4.12	3.17	3.45
M_{in} [g]	5.54	5.54	3.34	3.25