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Evaluation of clogging in HSF pilot-scale CWs using tracer experiments

G.D. Gikas[1*], V.A. Papaevangelou[1], K. Moutsopoulos[1] and V.A. Tsihrintzis[2]
[1] *Laboratory of Ecological Engineering and Technology, Department of Environmental Engineering, School of Engineering, Democritus University of Thrace, 67100 Xanthi, Greece*
[2] *Centre for the Assessment of Natural Hazards and Proactive Planning & Laboratory of Reclamation Works and Water Resources Management, School of Rural and Surveying Engineering, National Technical University of Athens, Athens, Greece*
[*] *e-mail: ggkikas@env.duth.gr*

Abstract: The worst operational problem that may occur during the operation of horizontal subsurface flow (HSF) constructed wetlands (CWs) is the clogging of the porous media. Clogging phenomena cause hydraulic malfunction, and therefore, may lead to inadequate performance of HSF-CWs, and finally, to the reduction of their lifetime expectancy. The main objective of the study was the investigation of clogging in HSF-CWs pilot-scale systems, and its influence on the hydraulics of these systems. Additionally, the study also aims at the evaluation of the sustainable operation of HSF-CWs after their long-term use. One HSF pilot-scale CW was used. The experiment was conducted using an impulse tracer test using KBr, which provided residence time distribution (RTD) curves, and generally, information regarding the effect of clogging on flow dynamics (possible short-circuiting, dead volumes, uneven distribution). For the conduction of the experiment, the conservative tracer was introduced at the inlet through the influent distribution system and the monitoring was performed at various points along the wetland bed (i.e., 1/3 and 2/3 of the length, and the outlet). Equations are used to compute, based on the tracer test data, the mean actual HRT, the tracer mass recovery, the normalized variance and the hydraulic efficiency. The results indicate that the unit operated smoothly without serious clogging phenomena. Generally, this system has shown a sustainable and successful long-term operation. The presented method is an effective method to evaluate performance of horizontal subsurface flow constructed wetlands in terms of clogging.

Key words: Constructed wetlands, Horizontal subsurface flow, Hydraulics, Clogging, Impulse tracer test, Potassium bromide

1. INTRODUCTION

Constructed wetlands (CWs) are vastly being used over the last decades throughout the world for the treatment of several wastewaters and the removal of various pollutants, such as nutrients, heavy metals, pesticides, organic substances, etc. (Wu et al., 2015; Papaevangelou et al., 2016a, 2017a, 2017b). This green technology offers many advantages against conventional treatment systems, such as easy and trouble-free operation, low maintenance and operational cost, tolerance to high flow and load variability, and use of natural energy sources (Kadlec and Wallace, 2009; Gkika et al., 2014). Horizontal subsurface flow (HSF) represent one of the most common types of CWs employed throughout the world. In HSF CWs, wastewater flows beneath the surface of the porous media in a fully saturated flow pattern (Kadlec and Wallace, 2009).

The worst operational problem that may occur during the operation of HSF-CWs is the clogging of the porous media (Pedescoll et al., 2011; de la Varga et al., 2013). As wastewater passes through the system, the removal of the pollutants occurs through several interactions between sediments, substrate, micro-organisms, litter, plants, atmosphere and the wastewater (Nivala et al., 2012; Gikas and Tsihrintzis, 2010; Kadlec and Wallace, 2009; Tsihrintzis and Gikas, 2010). Several mechanisms, including biological, physical and chemical develop and eventually lead to the saturation and the gradual clogging of the porous media (Pedescoll et al., 2011; Nivala et al., 2012; Pozo-Morales et al., 2013). Clogging phenomena cause hydraulic malfunction, and therefore, may lead to inadequate performance of HSF CWs and to the reduction of their lifetime expectancy (Caselles-Osorio et al., 2007; Pedescoll et al., 2011; Nivala et al., 2012; de la Varga et al., 2013).

There are several ways of evaluating the extent and severity of clogging in a wetland environment, including: hydraulic conductivity measurement and tracer studies (Nivala et al., 2012). The main objective of the study was the investigation of clogging in HSF-CWs pilot-scale systems and the eventual influence on the hydraulics of these systems with the use of an inert impulse tracer. Additionally, the study also aims at the evaluation of the sustainable operation of HSF-CWs after their long-term use.

2. MATERIALS AND METHODS

2.1 System configuration

The research was conducted at the outdoor facilities of the Laboratory of Ecological Engineering and Technology, Department of Environmental Engineering, Democritus University of Thrace (location 41º08'47"N, 24º55'09"E). Specifically, the experimental area included a horizontal subsurface flow pilot-scale constructed wetland, which has been described in detail by Akratos and Tsihrintzis (2007). The HSF CW (unit code name: MG-C) was a rectangular tank with dimensions 3 m long, 0.75 m wide and 1 m deep, filled with medium gravel (MG; D_{50} = 15.0 mm, range 4–25 mm) as porous media at a thickness of 45 cm, and planted with *Typha latifolia* (Figure 1). The unit was constructed in 2003 and has been in operation since then in the conduction of several experiments (e.g., see Akratos and Tsihrintzis, 2007; Stefanakis et al., 2009a; Stefanakis and Tsihrintzis, 2009b; Stefanakis et al., 2011; Papaevangelou et al., 2012, 2016b, 2017a). Therefore, this study attempts to assess the hydraulic conditions and efficiency in this pilot-scale HSF CW after its long-term use, and observe the extent of clogging over time.

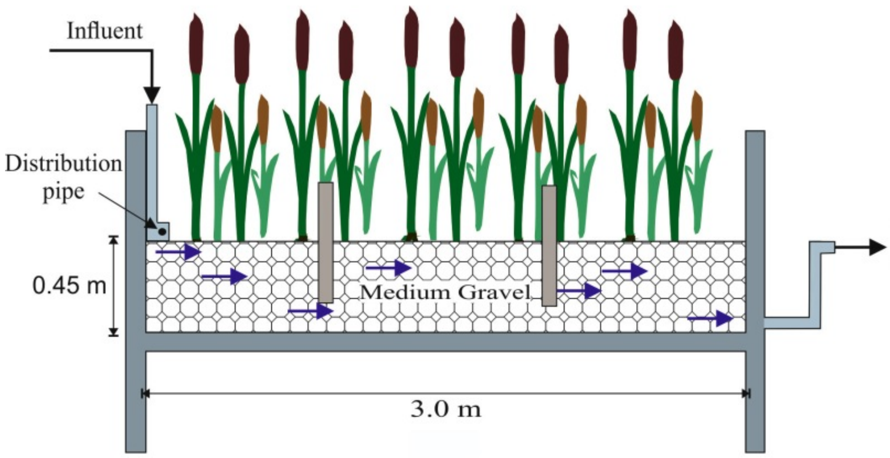

Figure 1. Schematic layout of the HSF-CW unit

2.2 Impulse tracer test

Hydraulic tracer tests are very useful not only in order to gain information regarding the hydraulic characteristics, but also to monitor the hydraulic regime and hydraulic efficiency. Any preferential flows or dead zones within the wetland environment can be identified through the introduction and the monitoring of a tracer throughout the wetland (Headley and Kadlec, 2007; Nivala et al., 2012). Two are the most common approaches of conducting a tracer experiment: either a single injection (impulse input) or a step injection (step input) (Headley and Kadlec, 2007). For the current study, the impulse technique was applied, because it requires both less quantity of tracer and less human labor.

There is a wide range of substances that can be used as tracers but three are the most popular choices; lithium cation, bromide anion and fluorescent dyes. Bromide and lithium are the most preferred choices due to their low cost and ease of analysis (Headley and Kadlec, 2007; Avila et al., 2016). In the current study, bromide was chosen, because it has a very low natural background and negligible sorption, it is highly soluble, and it is not susceptible to degradation (Lange et al., 2011; Avila et al., 2016).

The tracer test was conducted in July 2014 by a single injection of bromide and the whole experiment lasted 8.5 days. The applied hydraulic loading rate (HLR) was 90 L per day, and the nominal HRT (nHRT) was 4 days. The daily feeding regime included 3 loadings (30 L each). The tracer solution was prepared by diluting approximately 2.26 g of potassium bromide (KBr) in 30 L of water (Table 1), which was completely dissolved, and was then introduced to the unit using a pump with a volume counter. The monitoring (sampling) started the same day 8 h after the tracer injection. Samples were collected every 8 hours from the effluent of the pilot-scale unit (Figure 1; Table 1). Bromide concentration was determined with the use of Ion Chromatography (IC 3000, Dionex). Before the beginning of the tracer experiment, the porosity of the substrate material was determined and was found to be 0.32.

Table 1. Data of the tracer experiment

Parameter	Value or Type
Type of tracer	Potassium Bromide, KBr
Type of injection	Impulse
Duration of the experiment, d	8.5
Time of injection of tracer	1st day (morning)
Amount of tracer (injected mass), g	2.26
Hydraulic loading rate (HLR), L/d	90
Nominal HRT (nHRT), d	4
Sampling points	Effluent of the CW
Sampling interval, h	8

2.3 Processing of data and calculation of statistical parameters

The nominal or theoretical HRT is calculated as follows:

$$\tau_n = \frac{V}{Q} = \frac{\varepsilon h A}{Q} \tag{1}$$

where: τ_n [d] is the nominal HRT; V [m^3] is the wetland water volume; Q [m^3/d] is the volumetric flow rate; ε [-] is the porosity of the substrate material; h [m] is the average water depth; and A [m^2] is the wetland surface area.

In order to evaluate the reliability of the tracer test, the recovery percentage Rr (tracer mass recovery) was calculated, using the following equation (Garcia et al., 2004). This parameter is an indicator of the lost mass:

$$Rr = \frac{\int_0^\infty Q(t)C(t)dt}{M_t} x100 \tag{2}$$

where: Q(t) [m^3/h] is the time-dependent flowrate function; C(t) [g/m^3] is the time-dependent exit tracer concentration function; and M_t [g] is the added tracer mass.

The average time (τ) the tracer particle or the water remains in the HSF wetland is referred as “mean actual HRT” or “tracer HRT” or “tracer detention time”. The variance (σ^2) describes the spread of tracer response curve about the mean actual HRT. τ and σ^2 are calculated by Eqs. (3) and (4), respectively (Headle and Kadlec, 2007; Kadlec and Wallace, 2009):

$$\tau = \frac{\int_0^\infty tC(t)dt}{\int_0^\infty C(t)dt} \tag{3}$$

$$\sigma^2 = \frac{\int_0^\infty (t-\tau)^2 C(t)dt}{\int_0^\infty C(t)dt} \tag{4}$$

and the normalized variance [-] is calculated by Eq. (5):

$$\sigma^2_\theta = \frac{\sigma^2}{\tau^2} \tag{5}$$

where: t [h] is the time; and the other parameters as defined above.

Persson et al. (1999) proposed the hydraulic efficiency λ parameter, which evaluates not only the effective volume utilization but also the tracer response curve. This parameter is calculated by Eq. (6):

$$\lambda = \frac{t_p}{\tau_n} \tag{6}$$

where: t_p is the time to the peak tracer concentration; and τ_n is the nominal HRT.

3. RESULTS AND DISCUSSION

The monitoring of the bromide concentration at the effluent of the pilot-scale CW unit provides the residence time distribution (RTD) response curve which is presented in Figure 2. The tracer (i.e., bromide) was detected at the outlet of the MG-C, after a delay time of 0.8 days (Figure 2). After a time of about 8.2 days, the tracer was not detected (Figure 2), and therefore, a time period of 8.2 days was enough to complete the experiment of the bromide injection. The values of statistical parameters, which were calculated as described before, i.e., using Eqs. (1) to (6), were 91%, 4.56 d, 2.18 d^2, 0.10, 3.5 d and 0.87 for Rr, τ, σ^2, σ^2_θ, t_p and λ, respectively. These parameters define the hydraulic behavior of the pilot-scale CW.

The tracer mass recovery rate Rr, as mentioned before, is an index which can evaluate the reliability of the tracer test, and it is considered acceptable if the values fluctuate between 80 and 120 % (Kadlec and Wallace, 2009). In tracer recovery rate calculation, the mean daily evapotranspiration (ET) rate in the MG-C was estimated at 13.8 (mm/d) based on Papaevangelou et al. (2012) method. The value of recovery rate was high and acceptable, as its value was 0.91, indicating that the experiment was carried out in a proper way.

The mean actual HRT (i.e., 4.56 days) in MG-C unit was greater than nHRT, which was 4.0 days. According to Hedley and Kadlec (2007), the actual HRT in the CW may be shorter than nHRT due to the existence of dead zones or, in other cases, longer due to incorrect measurement of flow rate and wetland volume. US EPA (2000) also reported that the mean actual HRT in many horizontal subsurface flow CWs was found to be from 40 to 80% less than the nHRT due to loss of pore volume. In the present study, the flow rate, the surface area and the porosity of the substrate material were directly measured, and therefore, the errors in the estimation of actual HRT were negligible. The results of the present study (i.e., value of mean actual HRT > nHRT) reveal that the loss of pore volume is negligible.

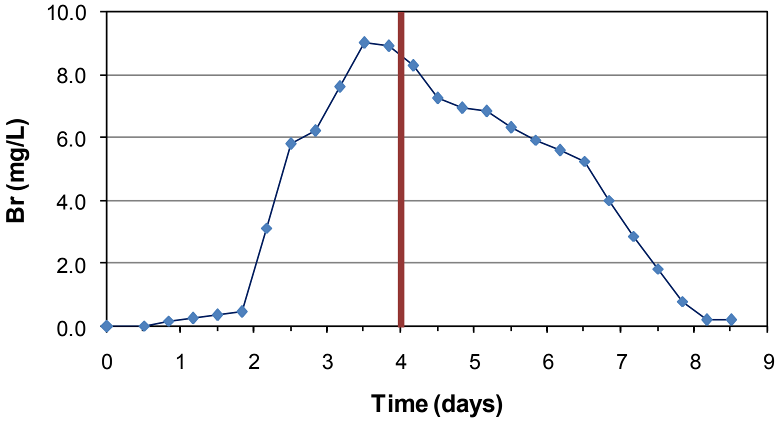

Figure 2. Tracer concentration in the effluent of the pilot-scale HSF CW. The vertical bar represents the nominal HRT (nHRT=4 days)

The variance (σ^2) of the RTD of the MG-C unit was 2.18 d^2 and the dimensionless variance of it was 0.10. Garcia et al. (2004), who investigated the effect of aspect ratio on hydrodynamics of horizontal subsurface flow CWs, reported that the shape of the RTD is affected by the aspect ratio. Also, according to US EPA (2000), the dispersion decreases with the increase of the aspect ratio. These statements explain the low values of dimensionless variance of the pilot-scale unit in the present study, since it has a high aspect ratio of 4.

According to Persson et al. (1999), the hydraulic efficiency parameter (λ), as mentioned before, indicates the existence of dead zones and short-circuiting in the wetland. The hydraulic behavior is categorized, depending on the λ value, into three groups, as follows: (1) for $\lambda > 0.75$, good hydraulic efficiency; (2) for $0.5 < \lambda \leq 0.75$, satisfactory efficiency; and (3) for $\lambda \leq 0.5$ poor efficiency. Based on these ranges, and taking into account the λ value for the pilot-scale unit which is 0.87, it can be concluded that the unit had a good hydraulic efficiency. The results indicated that the unit operated smoothly without important clogging phenomena.

4. CONCLUSIONS

A procedure was developed and applied, based on impulse tracer test, to evaluate clogging in a horizontal subsurface flow constructed wetland. Potassium bromide was used as a conservative tracer, which proved to be a good option, showing low mass loss along the experimental CW. Equations have been presented to compute, based on the tracer test data, the mean actual HRT, the tracer mass recovery, the normalized variance and the hydraulic efficiency. Based on these, the evaluation of clogging is possible.

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