Ecological Engineering 116 (2018) 21–30

Contents lists available at ScienceDirect

Ecological Engineering

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

The influence of grain physicochemistry and biomass on hydraulic conductivity in sand-filled treatment wetlands

P.J. Welz[a], W. Mbasha[b], I. Smith[a,b], G. Holtman[a,b], G. Terblanche[a], M. Le Roes-Hill[a], R. Haldenwang[b,*]

[a] Biocatalysis and Technical Biology Research Group, Institute of Biomedical and Microbial Biotechnology, Cape Peninsula University of Technology, Bellville Campus, PO Box 1906, Bellville, Cape Town 7535, South Africa

[b] Department of Civil Engineering, Cape Peninsula University of Technology, Bellville Campus, PO Box 1906, Bellville, Cape Town 7535, South Africa

ARTICLE INFO

Keywords:
Constructed wetland
Treatment wetland
Flow
Hydraulic conductivity
Clogging
Sand

ABSTRACT

The flow of effluent through treatment wetlands is influenced by the infrastructure set-up, the effluent character, the type of hydraulic flow, the mode of operation, the type of substrate, and the type and quantity of biomass. Current flow models have not been well validated, and/or do not accurately account for biomass clogging. In this study, treatment wetlands containing Dune or River sand with similar particle size distributions exhibited significant disparities in achievable flow rates. To gain insight into this phenomenon, further investigations were conducted to compare: (i) sand particle characteristics (size, elemental and mineral composition, grain morphology), (ii) the relationships between mineral composition and shape of the sand particles, (iii) the hydraulic conductivity of the different sand types before and after inducement of biomass growth, and (iv) the measured hydraulic conductivities with those predicted using the fractional packing Kozeny-Carman model.

Using automated scanning electron microscopy (QEMSCAN™) it was determined that the shape of the quartz particles of the River sand (98% quartz) and calcite particles of the Dune sand (81% quartz, 18% calcite) were less round and more angular than the quartz particles of the Dune sand, and that the River sand particles were conglomerate in nature and/or fractured. The hydraulic conductivities of the Dune and River sands were significantly different (0.284 and 0.015 $mm\,s^{-1}$, respectively), and the hydraulic conductivity of the Dune sand decreased by 51% due to biomass accumulation. The fractional packing model overestimated the measured values.

1. Introduction

Treatment wetlands (TWs), alternatively termed constructed wetlands (CWs), are engineered systems that mimic natural wetlands. TWs are used for the bioremediation of a variety of domestic and industrial wastewaters. The bio-physical environment of these systems consists of three main components that function synergistically during effluent treatment, namely plants, microorganisms and a physical substrate (Sanchez, 2017). The flow of effluent through TWs is affected by the infrastructure set-up (e.g. slope, location of inlet/s and outlet/s), the effluent character, the type of hydraulic flow (vertical/horizontal, surface/subsurface), the mode of operation (intermittent/continuous), the type and quantity of biomass (microbial and botanical), and the physical substrate (Rios et al., 2009; Sanford et al., 1995; Suliman et al., 2006).

The most commonly used physical substrates are gravel and sand, and there are advantages and disadvantages to each. Notably, if the flow is entirely reliant on the media, the smaller diameter of sand particles will result in a higher hydraulic retention time (HRT) than a gravel-filled system; sand also affords a larger total surface area for biofilm attachment (Knowles et al., 2011). However, sand-filled TWs have smaller intrapore spaces, and are therefore more prone to clogging than their gravel-filled counterparts (Akratos and Tshrintziz, 2011; Knowles et al., 2011). Some TWs use a combination of layers with soil/sand, stones and gravel. This adds to the complexity of the HC but also reduces clogging (Ranieri et al., 2013). Understanding the hydraulic properties of different sand types is key to the successful design and operation of these TWs.

The saturated hydraulic conductivity (HC) is an intrinsic value (k) that describes the speed at which fluid is capable of moving through a

Abbreviations: BSF, biological sand filter; CW, constructed wetland; HRT, hydraulic retention time; HC, hydraulic conductivity; OLR, organic loading rate; PSD, particle size distribution; SSFR, saturated system flow rate; SWW, synthetic winery wastewater; TW, treatment wetland

* Corresponding author.
E-mail address: haldenwangr@cput.ac.za (R. Haldenwang).

https://doi.org/10.1016/j.ecoleng.2018.02.017
Received 25 July 2017; Received in revised form 5 January 2018; Accepted 24 February 2018
Available online 05 March 2018
0925-8574/

saturated environment. On a macro scale, the porosity and the manner in which the intrapore space is distributed in the substrate are the most important determinants of HC (Morin, 2006). At a micro scale, it has been shown that the HC generally increases with increased particle size, and decreases as particles become more uniform in size i.e. well-graded sand (Giraldi et al., 2009; Suliman et al., 2006). Indeed, models of hydraulic flow in TWs are often based on parameters solely derived from the particle size distributions (PSDs) (Cho et al., 2006; Salarashayeri and Siosemarde, 2012). However, unless the particles are spherical, the geometry of grains can also have a significant influence on the HC because the porosity and tortuosity is dependent on inter-particle contact (packing) (Morin, 2006; Narsilio et al., 2010; Urumović and Urumović, 2014). In reality, all the intrinsic properties of the sand (particle size distribution, particle shape, and mineralogy) can play important roles in determining the achievable flow rate in TWs (Bruch et al., 2014; Pedescoll et al., 2009).

To confound the situation further, the HC in TWs alters significantly after start-up due to the growth of functional biomass and/or clogging by solids from wastewater and/or dissolution of TW material (Matos et al., 2017; Serrano et al., 2010; Welz et al., 2011). After start-up, biomass clogging is initially progressive, and then typically stabilises within an operational range (Zhao et al., 2009). The magnitude of this range depends on the variability of the operational parameters, notably the organic loading rate (OLR) (Matos et al., 2017; Zhao et al., 2009). The microbial community structure, and therefore biofilm structure in TWs is strongly influenced by the type of effluent, the hydraulic flow type, and the type of sand (Carson et al., 2007; Liu et al., 2017; Girvan et al., 2003; He et al., 2014; Welz et al., 2014a), and it has been demonstrated that the introduction of bacterial strains that produce high amounts of expolysaccaharides lead to increased biofilm clogging (Vandevivere and Baveye, 1992). There are substrate degradation models that predict the extent of microbial growth, and/or the concurrent changes in flow rates in TWs (e.g. Aiello et al., 2016; Brovelli et al., 2009; Samsó and Garcia, 2013; Samsó et al., 2016; Stewart and Kim, 2004). However, none of the models predicting changes in HC have been widely validated because of insufficient experimental data (Samsó and Garcia, 2013; Samsó et al., 2016). As the microbial populations in biological wastewater treatment systems are constantly in a state of flux, there is a need for more empirical data on the extent of biomass clogging in sand-filled TWs treating various types of effluent.

This manuscript describes a series of studies used to understand the influence of sand grain mineralogy on the shape and packing of sand particles in TWs treating synthetic winery wastewater (SWW), and how these relate to the HC and flow. Initial studies were conducted using unplanted experimental sand-filled TWs [alternatively named biological sand filters (BSFs)] to treat SWW. It was found that different sand types with similar PSDs exhibited extreme disparities in achievable flow rates. This prompted investigations to determine and compare (i) the characteristics of the sand particles (size, elemental and mineral composition, grain morphology), (ii) the relationship between mineral composition and shape of the sand particles, (iii) the measured HC of the different sand types before and after inducement of biomass growth using dedicated columns, and (iv) the measured HC values with those predicted using the fractional packing Kozeny-Carman model.

2. Materials and methods

2.1. Determination of saturated system flow rates in biological sand filters (unplanted, sand-filled treatment wetlands)

2.1.1. Experimental systems treating synthetic winery wastewater

Experimental BSF replicates were set-up as shown in Fig. 1A and operated in batch mode (fill and drain). Over the period 2009–2012, a number of experiments were conducted using four replicates containing either River, Dune, or a mix of Dune and River sand (Mix) used to treat synthetic winery wastewater (SWW) (e.g. Ramond et al., 2013; Rodriguez-Caballaro et al., 2012; Welz et al., 2011, Welz and Le Roes-Hill, 2014, Welz et al., 2014b). Due to differences in flow rates, the replicates containing River sand were allowed to drain freely, while those containing Dune and Mix sands were plugged at the outlet before feeding to increase the HRT. The flow of effluent from the experimental BSFs was defined as the saturated system flow rate (SSFR) and measured in L hr^{-1} $m^3 sand^{-1}$. This parameter was calculated by measuring the volume of effluent flowing from the outlets of the systems for a pre-determined period. In the case of the systems containing River sand, the measurements were taken 1 h after feeding, while for the other systems, measurements were taken immediately after unplugging. This protocol, as well as the pre-determined period of measurements differed for each sand type, and were individually established to ensure the most accurate and reproducible readings (300 s, 90 s and 180 s for River, Dune and Mix sands, respectively) (P.J. Welz, unpublished data).

2.1.2. Pilot winery wastewater treatment system

Following experiments using SWW (Section 2.1.1), a novel pilot system was installed and operated to treat cellar effluent at a small winery in the Western Cape, South Africa. The system consisted of four functional modules (sand-filled polyethylene tanks identical to the experimental replicates) as well as related infrastructure (Fig. 1B). A total of 7.26 m^3 of Dune sand was contained in the system, which was operated in continuous sub-surface flow mode. Influent was pumped using a solar-powered pump from an existing settling basin into a series of two holding tanks from where it was gravity fed through the modules back to the settling basin. The modules were operated in parallel, with the inflow being controlled automatically using valves and balancing tanks. The OLR in TWs is typically expressed in terms of surface area. We believe that this is not valid because it does not take the depth of the system into account. We have therefore expressed the OLR using both the total volume of sand and the surface area. The OLR was 167 gCOD m^3 sand day^{-1} (average) with a range of 32–338 gCOD m^3 sand day^{-1} [280 gCOD m^2 sand day^{-1} (average) with a range of 53 to 568 gCOD m^2 sand day^{-1}].

The SSFR of the pilot-scale system was determined by taking triplicate measurements of the flow from the final outlet over the period of one minute. The correlation between influent COD and SSFR was determined using Dell Statistica.

2.2. Determination of hydraulic conductivity (k) using columns

2.2.1. Set-up and operation of columns

Three experimental columns were manufactured and set-up (Fig. 1C). These consisted of acrylic columns (ø 0.3 m) supported on mild steel legs welded to rolled flat bars, with steel mesh welded to the bottom of the rolled flat bars to support aggregate. In turn, the aggregate supported sand (0.6 m height). Mild steel buckets fitted with nipples and isolating valves were welded to the bottom of the stands and used to drain fluids and regulate head conditions. Peristaltic pumps were used to pump influent to perforated buckets that gently and evenly dissipated influent to the columns.

2.2.2. Calculation of hydraulic conductivity by the constant head method

The HC, also known as the co-efficient of permeability (k) of River, Dune and Mix sands were determined by the constant head method i.e. by measuring the actual flow of influent through the columns under various constant head conditions. A product of Darcy's Law, presented by Eq. (1) was used to calculate the HC

$$k = \frac{vL}{tAH} \quad (1)$$

Where (k) *is* the coefficient of permeability, (V) is the volume of effluent, (L) is the height of the sand, (t) is the effluent collection time, (A) is the area of the sand, and (H) is the total head.

Once the pumping rate was calibrated to obtain a specific constant