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Solids distribution and hydraulic conductivity in multi-cell horizontal subsurface flow constructed wetlands

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ABSTRACT

This study evaluated the accumulated solids spatial distribution and their relationship with hydraulic conductivity (*K*) in a multi-cell horizontal subsurface flow (HSSF) constructed wetland (CW). The system is located near the Caribbean Coast of Colombia where tropical conditions reign. After three years of operation, total suspended solids (TSS) and volatile suspended solids (VSS) accumulated within the interstitial spaces and those that adhered to the surface of the gravel were quantified. Samples were collected at six points and at two depths (0.1 and 0.35 m) within each of five cells of the CW. Similar quantifications were made three months after a washing process of the granular bed. The average values for the first samples collected were 3.129 kg m^{-2} TSS and 35.5% VSS. The average values for the second samples collected were 0.224 kg m^{-2} TSS and 42.7% VSS. *K* values were measured after the gravel washing process using the falling head method. *K* values registered above 400 m d^{-1}, which coincided with the low amount of accumulated TSS (<1 kg m^{-2}). This assessment revealed an inverse relation between accumulated solids and hydraulic conductivity ($R^2 = 0.76$), indicating that the accumulation rate of solids was the primary factor causing clogging within the constructed wetland treatment cells. In order to evaluate the state of clogging in tropical constructed wetlands, a dimensionless number was proposed as an indicator of clogging severity.

1. Introduction

One of the primary concerns related to Horizontal Sub Surface Flow Constructed Wetlands (HSSF CW) systems is their propensity to clog due to the progressive accumulation of solids in the void spaces of gravel medium. The clogging matter consists of hydrated gels and sludge composed of organic and inorganic solids (Knowles et al., 2010). Clogging initially occurs in the inlet zone by the mineral and refractory sediments accumulation and chemical precipitates sedimentation. For these reasons, the greatest reductions in hydraulic conductivity occur in this zone (Kadlec and Wallace, 2009). As clogging ensues, hydraulic behavior changes, short-circuiting occurs, and ultimately treatment efficiency can be significantly diminished (Knowles et al., 2011). When clogging is severe, wastewater will follow the path of least resistance, including water flooding to the surface of the wetland. Under extreme conditions, this process can induce surface-flow hydraulics. As surface-flow episodes increase, short-circuiting intensifies causing that hydraulic retention time and treatment efficiency decrease (Lancheros et al., 2013; Pedescoll et al., 2009). The hydraulic conductivity in CWs is a critical variable that reflects the ability of water to flow through a planted bed of porous media, which value is high at the beginning of operation and will decrease with the accumulation of solids in the gravel bed (Kadlec and Wallace, 2009).

The main variables that control long-term hydraulic behavior and treatment efficiency in subsurface flow (SSF) wetlands include good pretreatment to remove suspended solids, a correct position and distribution of influent and effluent manifolds, wastewater organic matter loading, hydraulic retention time and hydraulic conductivity of the gravel matrix (Knowles et al., 2010; Wang et al., 2010). Studies have been conducted to evaluate spatial and temporal dynamics of clogging according to hydraulic and solids loading rates (Rodgers and Mulqueen, 2006; Sanford et al., 1995). Standard protocols have been developed to evaluate the degree of clogging by measuring hydraulic conductivity (Caselles-Osorio et al., 2007; Knowles and Davies, 2009) and more recently the microbial fuel cell use could be a great potential for continuous clogging assess-

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Table 1
Climatic characteristic of study area (Northeastern Colombia) where treatment systems were located.

Characteristics (Units)	Valor, Units
Temperature (°C)	28–32
Height (M.A.S.L.)	320
Precipitation (mm)	1800
Relative humidity (%)	>78
Wind ($m\,s^{-1}$)	3
Sunshine ($h\,month^{-1}$)	228

ment (Corbella et al., 2016). However, improved measures need to be developed to control clogging via engineering design and operations management, since repairs to clogged wetlands (washing and/or replacement of gravel substrates), can be very costly (Knowles et al., 2011; Nivala et al., 2012; Pedescoll et al., 2009). Therefore, in practical terms, if surface flow is observed above the SSF CW bed, a measure of hydraulic conductivity could help to correct the problem without repairing and cleaning the whole wetland. Moreover, information about clogging of horizontal sub surface flow constructed wetlands and design criteria especially suited to tropical regions are required since this technology is not yet widely used there (Caselles-Osorio et al., 2011). The objectives of this study were to evaluate the influence of solids loading rate and hydraulic conductivity on the degree of clogging in a pilot-scale multi-cell HSSF CW located in a tropical country. The pilot HSSF CW operated for three years and then the granular material was removed and washed to improve its functioning.

2. Methodology

2.1. Treatment system, location, conditions, and background

The study was conducted on a HSSF CW which served a home of seven (7) inhabitants and a small restaurant near the town of Bonda in northeastern Colombia, 15 km from the Caribbean Coast. The general characteristics of the study area are shown in Table 1. The treatment system consists of a 2.6 m^3 septic tank followed by a HSSF CW with five cells connected in series (Fig. 1). Each cell had 1 m^2 of surface area, 0.5 m of depth, and backfilled with river gravel substrate (average diameter 10–12 mm and 34.5% of porosity). Following the CW cells, the water flowed by gravity into a small surface flow cell (2 m × 0.9 m × 0.5m). Finally, the treated water flowed into a terminal cell (1 m × 0.9 m × 0.5m) for storage and reuse.

The average influent flow rate during the first two years of operation ranged from 0.42 $m^3\,d^{-1}$ to 6.7 $m^3\,d^{-1}$ and the average organic loading rate was 15 g COD $m^{-2}\,d^{-1}$ (Caselles-Osorio et al., 2008). During the third year of operation the flow rate averaged 5.2 $mL\,s^{-1}$ with nominal retention time of 1.9 d and average organic loading rate was 30 g COD $m^{-2}\,d^{-1}$ (Lancheros et al., 2013).

2.2. Accumulated solids and clogging time calculations

After the initial three years of CW operation, accumulated solids adhering to the gravel and within the interstitial voids were sampled at discrete locations within each treatment cell to monitor clogging development with respect to TSS and VSS. Samples were collected at six points and at two depths (0.1 and 0.35 m) within each of five cells of the CW. Three months after washing the gravel substrate, identical sampling and measurements were repeated.

Fig. 2 depicts the sampling locations and depths in each of five cells. Gravel samples were collected using a metal pipe (114 mm in diameter and 700 mm long), which was forced into the gravel using a mallet. The gravel and adhered solids contents of the tube were slowly removed incrementally from the top down taking care to minimize turbulence and scouring of solids from the gravel. Samples were collected at depths of 10 and 35 cm and interstitial water samples were collected separately. 100 g of each gravel sample were immersed in 149 mL of tap water and sonicated for seven minutes using a Branson Model 3200 unit. The accumulated solids were calculated as the sum of the interstitial and adhered solids. Accumulations of TSS and VSS were quantified for each discrete location and depth within the gravel matrix according to APHA-AWWA-WEF (2012) and Caselles-Osorio et al. (2007).

To determine the clogging time (CT) in wetland beds for solids accumulation of the experiment, the following equations were used (Kadlec and Wallace, 2009):

$$CT = a\frac{\rho_{solid}}{qC_{TSS_i}} \quad (1)$$

$$a = 150\varepsilon d \quad (2)$$

Where,
CT = Clogging time
a = empirical coefficient, m
ε = clean porosity,
d = particle diameter, m
ρ_{solid} = bulk density of accumulating solids, kg m^{-3} (m^{-3} as bed volume)
q = hydraulic loading rate (HLR), m d^{-1}
C_{TSS_i} = inlet TSS concentration, kg m^{-3}

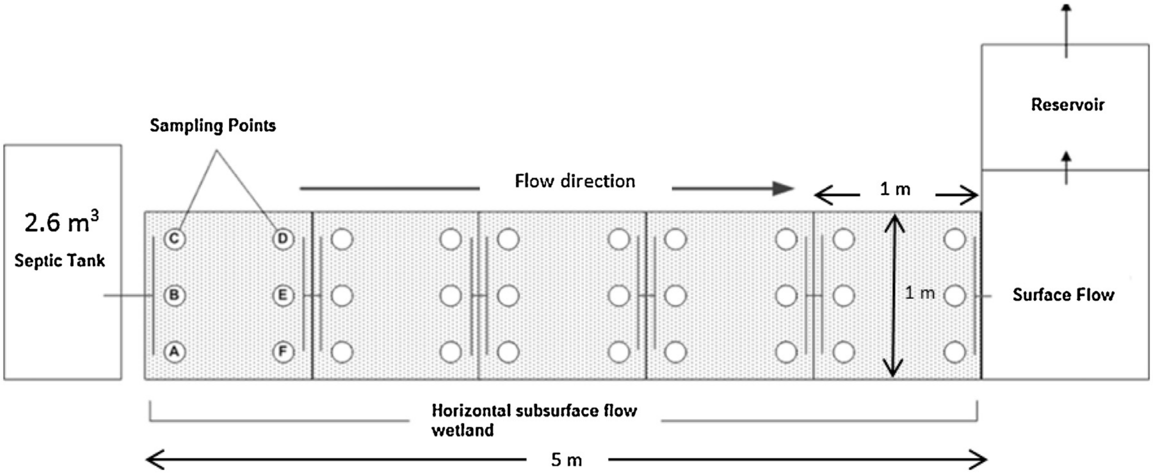

Fig. 1. Schematic of horizontal sub-surface flow constructed wetland cells and location points for sampling solids and hydraulic conductivity.