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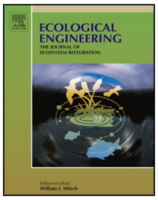

Influence of hydraulic loading rate, simulated storm events and seasonality on the treatment performance of an experimental three-stage hybrid CW system

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ABSTRACT

An experimental hybrid system based on an anaerobic reactor followed by three stages of different constructed wetland configurations was evaluated when operating under a high hydraulic loading rate (HLR = 0.27 m d^{-1}, considering the area of the VF beds) for one year, which corresponds to four times the nominal hydraulic loading rate, with the purpose of reducing the specific area required. Moreover, in order to assess its buffer capacity, a major storm event was simulated by increasing the HLR 10 times during 1 h. A tracer experiment was also performed to determine the experimental hydraulic retention time (HRT). The system consisted of a hydrolytic upflow sludge blanket (HUSB) reactor followed by two alternating 1.5 m^2 vertical subsurface flow, a 2 m^2 horizontal subsurface flow and a 2 m^2 free water surface constructed wetlands operating in series. The system achieved very high values of removal of solids, organic matter and nutrients (82, 93, 96 and 75% for COD, BOD$_5$, TSS and NH$_4$-N, respectively). Removal of PO$_4$-P and SO$_4{}^{2-}$ were though fairly low, of 11 and 10%, respectively. There was a seasonal effect in the system for parameters whose removal highly depends on biodegradation, being enhanced under warmer conditions (98 and 92% removal of BOD$_5$ and NH$_4$-N in summer vs. 87 and 67% removal of BOD$_5$ and NH$_4$-N in winter). The experimental HRT of the entire system was of about 38 h, which is greater than the theoretical HRT (28 h). During the simulation of the storm event removal efficiencies did not vary significantly from the ones obtained under normal conditions (average of 83, 99 and 80% for COD, TSS and NH$_4$-N removal, respectively). The system showed a very good buffer capacity coping with sharp fluctuations in flow to be treated, showing to be an adequate solution for wastewater treatment in small communities. The specific area requirement under the long-term operation showed to be as low as 2 m^2/PE.

1. Introduction

In recent years there has been a substantial progress in the implementation of wastewater treatment systems around the world. The sanitation model generally practiced consists of the development of extensive collection systems directing wastewater into a centralized treatment plant. This has a very high cost and requires a high energy demand, including procedures which are often highly complex. Although in large urban areas of industrialized countries the lack of space and the high flow make the use of conventional systems irreplaceable, at small-scale a paradigm shift is necessary, in which a decentralized approach has to predominate. This requires finding alternative technologies that present great versatility and adaptability, good integration in the natural environment, and costs of implementation and operation well below those produced in the conventional treatment of urban wastewater.

In this sense constructed wetlands (CWs) represent a tool to facilitate the transition to this new model. The infrastructure needed for its construction is very simple and affordable, and operation and maintenance are relatively easy and inexpensive. They have low or no energy consumption, low sludge production, and do not require the addition of chemical reagents. In addition, these systems provide habitat for wildlife and in consequence increase biodiversity, thus they can be implemented to restore degraded areas. They are also resilient to large fluctuations in water quality and flow, as well as air temperature (Ávila et al., 2013c). Considering these treatment systems are based on the knowledge of the functioning of natural systems, it is a very appropriate

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technology for its application in developing countries since they do not generate technological dependence (García et al., 2010; Kadlec and Wallace, 2009). What is more, wetlands can be constructed using local materials and labor, which is also a great attribute to these countries.

There are different wetland types depending on the flow type, which can be divided into subsurface flow (which include vertical and horizontal subsurface flow wetlands, depending on the direction of the flow) and surface flow (which has a free water table on top of a soil). Each wetland type is especially good at promoting specific mechanisms due to the different physico-chemical characteristics taking place within each configuration. Indeed, wetlands can be combined in series constituting hybrid systems where advantages and disadvantages of each wetland type can balance each other out (Vymazal, 2013). There exist various hybrid CW systems in the world, both at experimental (Ávila et al., 2013a, 2014b; Herrera-Melián et al., 2010; Tunçsiper, 2009) and at full-scale (Ávila et al., 2013c, 2014a; Ayaz et al., 2012, 2015; Masi and Martinuzzi, 2007; Öövel et al., 2007), showing to be highly effective in removing a wide range of contaminants, including recalcitrant substances, and oftentimes producing a final effluent which can be reused.

The removal of contaminants in CWs occurs as a result of complex physico-chemical and microbial interactions. The rates of these processes depend on a variety of design and operational factors, as well as environmental conditions and inflowing wastewater quality (Ávila et al., 2013b, 2014c; Button et al., 2014; Paing et al., 2015). These include parameters such as type of primary treatment, depth of the bed, hydraulic loading rate or feeding strategy, among others. One of the key parameters is the type of primary treatment, whose implementation before constructed wetlands is strongly recommendable in order to reduce solids loading applied to the wetland, which may cause clogging and reduce the lifespan of the system (Pedescoll et al., 2011a). This typically consists of settlers, septic or Imhoff tanks (Puigagut et al., 2007), mainly physical treatments, which have a removal efficiency of ca. 30–40% for biochemical oxygen demand (BOD) and ca. 50–60% for suspended solids (Tchobanoglous and Burton, 1991). Recently, anaerobic reactors have been used as primary treatment. The upflow anaerobic sludge blanket (UASB) and hydrolytic upflow sludge blanket (HUSB) reactors are good alternatives to conventional primary treatment since they are able to produce effluents with fairly lower concentrations of organic matter and suspended solids (up to 80% removal) (Álvarez et al., 2008; Barros et al., 2008; Díaz et al., 2008; Dornelas et al., 2009). In a HUSB reactor the water circulates upwardly through a sludge bed maintained under anaerobic conditions. These are essentially UASB reactors operated at a lower hydraulic retention time (HRT) (from 2 to 7 h) in order to avoid methanogenesis as much as possible, but instead promoting the hydrolysis of organic matter, thus helping preventing or delaying clogging processes. In general, solids retention time in HUSB reactors is maintained for over 15 days in order to achieve high hydrolysis rates (Pedescoll et al., 2011a,b; Ruiz et al., 2008).

However, depending on design, CWs usually require a larger land area than conventional treatments. In fact, the specific area needed for CWs system was estimated to be around 5–6 (Kadlec and Wallace, 2009) and 2–3 (Molle et al., 2008) m^2/PE for HF and VF CWs, respectively, which is much higher than that required by conventional wastewater treatment technology (much less than 1 m^2/PE) (Veenstra et al., 1997). Moreover, the presence of major storm events could hinder the correct functioning of these systems, especially in tropical and subtropical areas where there is a predominant rainy season. Indeed, only few studies assessed the robustness of CWs during heavy rainfall events (Ávila et al., 2013c).

An experimental three-stage hybrid CW system was previously monitored while operating at a design hydraulic loading rate (HLR) of 0.06 $m\,d^{-1}$ and also under punctual HLRs of 0.13 and 0.18 $m\,d^{-1}$ (taking into consideration only the area of VF beds, i.e. 3 m^2) (Ávila et al., 2013a, 2014b). The results suggested that the system could be capable of handling much larger loads, and therefore the main goal of this study was to evaluate the treatment performance of the hybrid CW system when operating under a very large HLR (0.27 $m\,d^{-1}$) in order to reduce the specific area required. For that purpose, the system was monitored during one year, and the seasonal influence was evaluated. Additionally, in the present study a major storm event was simulated and its impact on treatment capacity was assessed. What is more, in order to estimate the hydraulic retention time a tracer experiment was conducted. Finally, this treatment plant was previously operated with an Imhoff tank as a primary treatment, but replaced by a HUSB reactor during this study period, so as to test whether it had a higher retention of solids.

2. Materials and methods

2.1. Description of the treatment system

The research was conducted in a treatment system which was set outdoors at the experimental facility of the GEMMA research group (Department of Civil and Environmental Engineering of the Universitat Politècnica de Catalunya-BarcelonaTech, Spain). This experimental plant consisted of a stirred storage wastewater tank, originally followed by an Imhoff tank but replaced by the time of this study by a HUSB reactor. This was followed by two VF CWs working in parallel, one HF wetland and, finally, one FWS wetland in series (Fig. 1). The system started operation in May 2010.

During the period considered in this study (April 2013–May 2014) the treatment plant operated at a constant input flow of approximately 800 $L\,d^{-1}$ (HLR = 0.27 $m\,d^{-1}$), which corresponds to 4 times the original design flow of 200 $L\,d^{-1}$ (Ávila et al., 2013a). The implemented value of HLR falls within the range of the highest values ever applied to VF wetlands reported in the literature, such as the 0.25 $m\,d^{-1}$ at Platzer (1999), the 0.295 $m\,d^{-1}$ implemented at Vymazal and Kröpfelová (2011), or the value up to 1.37 $m\,d^{-1}$ reported at Arias et al. (2003).

Urban wastewater from a nearby municipal sewer was daily pumped into a raw wastewater tank before it flowed into a HUSB reactor (0.25 m^3), which had an internal diameter of 0.44 m and a useful height of 1.7 m. The nominal HRT was of 7.5 h (for a flow of 800 $L\,d^{-1}$). This reactor was equipped with 8 taps, positioned vertically in series, starting at a height of 40 cm and each one located at a distance of 20 cm from each other. This distribution made possible the regulation of the level of the sludge bed inside the reactor by opening the taps and discharging a part of the sludge layer. In order to accelerate the correct operation of the HUSB reactor and the stabilization of the sludge layer, it was inoculated with secondary sludge from a full scale wastewater treatment plant (Gavà, Catalonia, Spain). In particular, 50 L of sludge were inoculated in order to achieve a desired concentration of volatile suspended solids (VSS) of 10 $g\,L^{-1}$, so as to ensure a proper operation. Effluent of the HUSB reactor flowed by gravity from tap 8 into a storage tank (0.2 m^3) and from this point water was conveyed into two parallel 1.5 m^2 VF beds alternating their operation in cycles of feed and rest (3.5 days each). These were intermittently fed by means of hydraulic pulses with a flow of around 30 L per pulse, resulting in about a pulse per hour. Effluent of VF beds was sent to a 2 m^2 HF wetland, and finally pumped into a 2 m^2 FWS wetland. Feeding of the HF and FWS units was done in a continuous mode by means of peristaltic pumps. All wetland units were constructed in polyethylene and were planted with *Phragmites australis* since the commissioning period, thus the vegetation was very well established during the time of the study. For specific design and operational parameters of the system the