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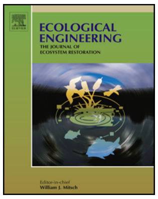

Experimental basis for the design of horizontal subsurface-flow treatment wetlands in naturally aerated channels with an anti-clogging stone layout

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ABSTRACT

An innovative design is presented of horizontal subsurface-flow treatment wetlands with high operational reliability against clogging; traceable metre by metre for modelling purposes. For two years, urban wastewater was treated in a full-scale wetland whose construction was based on conclusions drawn from laboratory tests. No clogging was observed. In contrast to existing designs, channel configuration is used for the plug-flow circulation of water, the bed has a longitudinal diagonal design of angular stones of decreasing size, and a circuit of forced natural ventilation is formed by the combination of wells and chimneys connected within an air chamber over the water surface. The cross-section values of influent load were four times higher than those traditionally employed. The stone diagonal splits the wetland into an upper region of aerated reactor and a lower region conveying water over a bed which works as an anaerobic digester, thereby demonstrating the importance of the circuit of aeration and of the gradient of hydraulic conductivity of the bed that adapts itself to the variation in the quality of the water along its course. Overloads and isolated halts fail to alter the oxidation-reduction potential since these biological systems present high inertia when faced with changes in feed supply.

1. Introduction

1.1. Background

The use of constructed wetlands for domestic wastewater treatment has become even more widespread in recent decades, despite the fact that their use dates back to the 1950s. These have shown themselves to be flexible systems which demonstrate: broad integration into the environment, enormous simplicity in application and operation; and no energy costs. In particular, since subsurface flow systems (SubSuperficial Flow Treatment Wetland, SSF TW) present no surface of water in contact with the atmosphere, they provide the additional advantages of incurring only a low risk of direct exposure to waste water and of the emergence of insects. These systems also minimize potential odours, and the thermal protection reduces water stratification, thereby preventing possible preferential flow (García et al., 2003). This makes them particularly suitable for use in small and medium-sized settlements.

Nowadays, however, their application is seen as threatened by the major problems arising from clogging, especially in those systems of horizontal flow (HSSF TW). Clogging leads to waterlogging, the by-pass of water, a generalized diminishment of the Hydraulic Retention Times (HRT), insufficiently treated effluents (Caselles-Osorio and García, 2007; Nivala and Rousseau, 2009), the generation of smells, infestations of mosquitoes, cause of the propagation of paludism in tropical countries, and the disuse of purification systems.

The magnitude of the problem has triggered a wide range of studies into the causes (Knowles et al., 2011; Nivala et al., 2012). These causes have been analyzed in order to introduce those changes deemed necessary for the development of reliable designs. In the present work, further innovations are introduced in a new model of HSSF TW, which has been installed in an experimental wastewater treatment plant in the south of Spain.

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1.1.1. Stone bed organization

The main obstructions in a HSSF TW are caused by a drastic reduction in the Hydraulic Conductivity (K_H), and hence this factor can be declared as a fundamental design parameter. The squared relationships of the Kozeny–Carman equation indicate that the hydraulic conductivity of a porous medium is highly sensitive to the size of the pores (Carman, 1937; Kadlec and Knight, 1996) and hence filler materials of low granulometry are especially prone to rapid obstruction through blockage of the filter pores (Blazejewski and Murat-Blazejewska, 1997; Langergraber et al., 2003; Platzer and Mauch, 1997; Wallace and Knight, 2006). For this reason, a gradual increment has been produced in the size of the stones of the beds used in HSSF TW (Iwema et al., 2005; Kadlec and Wallace, 2009; USEPA, 2000; Wallace and Knight, 2006). The distribution of the size of the particles in the bed and even their shape also influence the hydraulic conductivity as indicated in the Ergun equation (Ergun, 1952).

In all the studies reviewed herein, the initial diminishment of hydraulic conductivity is due to the sedimentation of particles of greater size and to the major development of biofilm. As water advances in the wetland, purification mechanisms via the biological degradation of organic material predominate over the sedimentation of solids, which is especially critical in the first few metres. It is a proven fact that the conductivity gradient in an HSSF TW is 60% less at the entrance than at the exit.

1.1.2. Geometry of the bed

On the other hand, we cannot ignore the importance of preventing the appearance of preferential paths and of dead, problematic and ineffective zones. By focusing special attention on the entrance as the principal zone of obstruction, the majority of authors recommend a uniform load of wastewater over the greatest horizontal surface possible, thereby establishing a limitation of horizontal load based on the correlations found between clogging and the load of the Total Solids in Suspension (TSS), and between clogging and organic matter (Winter and Goetz, 2003). In this way, the recommended system is that in which the width exceeds or equals the longitude. However, in these cases, the distribution of water is converted into a further problem whereby continuous obstructions and non-uniform loads are observed (Murphy and Cooper, 2010). The workings of a plug-flow reactor also guarantee that the whole volume is put to good use and that no dead zones exist. To this end, the distribution of water to be treated takes on particular significance in this study.

1.1.3. Microbial processes

Once the bed configuration has been dealt with, it is necessary to act on a third factor; the bacterial populations that work inside the stone bed.

Traditionally, it has been assumed that the organic material decomposes sufficiently and in such a way that only the inorganic solids contribute towards clogging. However, the enormous variability in the rate of decomposition of organic matter, the highly colloidal properties of certain humic compounds, together with the hydrophilic properties of these compounds (Christensen et al., 1998; Nguyen, 2000) with approximately 80% in volume of water (Tanner and Sukias, 1995), all constitute a major potential for the blockage of pores by organic matter that, in general, is satisfactorily degraded.

One should also take into account the role of the material density since the porosity loss attributable to the accumulation of inorganic solids (about 2.500 kg/m^3 density) may amount to 1–3% of the pores (Llorens et al., 2009). However, the complexation with small amounts of biological material can form a low-density gelatinous sludge with high water-retention capacity (IWA, 2000; Kadlec and Watson, 1993; Tanner et al., 1998). Organic matter of 30–300 kg/m^3 density increases the occlusion of the effective pores to between 27% and 77% (Llorens et al., 2009); these circumstances are also given at low redox potential (Kadlec and Watson, 1993). Density values of sludge in the inlet region, which are four times lower than in the outlet region (60 kg/m^3 against 240 kg/m^3), are doubly efficient in reducing the porosity and therefore clog the bed (66% versus 28% occlusion) (Llorens et al., 2009) when they reach the lowest values of hydraulic conductivity (20 m/day as opposed to 45 m/day), (Pedescoll et al., 2009).

It is shown that the biofilm that colonizes the stones inside the HSSF TW excretes a polymeric sludge (Madigan et al., 2006), is analogous to a gel (Rittman and McCarty, 1980; Tanner and Sukias, 1995), is relatively impermeable (Taylor et al., 1990; Vandevivere and Baveye, 1992a,b,c), and carries a high water content. An excessive rise in the anaerobic conditions of the system, methanogenic bacteria (such as *Alcalígeneseutrophus and Bacillusmegaterium*) produces an excessive synthesis of polyhydroxybutyrate (PHB), apparently in response to physiological stress conditions as an energy reserve and of organic chain formation for cell biomass (Gaudy and Gaudy, 1980). The PHB exudates have flocculent properties, generally giving rise to mucins, and are derived with the subsequent formation of a biofilm that traps molecules, bacteria, suspended solids, minerals redissolved by bacteria, and phosphate precipitates (Maqueda et al., 1994) which eventually clogs the system (Pozo-Morales et al., 2013). In traditional HSSF TW, the wetland is saturated with water, which displaces the air in the pores in such a way that the degradation of the organic matter principally occurs through an anaerobic process (Salas and Pidre, 2007). The described circumstances concur at low oxidation potentials.

Vertical flow wetlands operate, in general, much more efficiently than do the horizontal wetlands and are less clogged due to their greater potential of aeration by means of air suction achieved through pulse injection (Cooper, 2005).

1.1.4. Modelling

In traditional wetlands, it is necessary to be extremely careful when talking about hydraulic conductivity values due to the fact that its values rarely reflect field measurements, and it remains impossible to monitor the system and the exact location of trouble spots since these reactors are inaccessible, stretch over large areas, and facilitate the occurrence of preferential paths. This lack of precision is, today, a barrier to the development of simulation tools (Langergraber, 2008) and therefore new experimental techniques are called for (Knowles et al., 2011).

1.2. Contribution of the article

The aim of this study is to establish the basis for the reliable design of an HSSF TW to overcome both the load limitation on wastewater input and traditional clogging problems. To this end, this study focuses on the optimization of the hydraulic conductivity of the medium, the geometry and the aeration of the system.

Considering the above, a modified wetland channel with natural forced aeration has been designed.

Since it is a proven fact that the decrease of the conductivity gradient in an HSSF TW may affect the porosity (Kozeny–Carman equations), then it appears illogical for the grain size (porosity), to be maintained constant throughout the medium. In this paper, the bed proposed passes from an initial porosity of 73% to 51% porosity at the output, that is to say, for predictable gradual decreases of up to 60% hydraulic conductivity, gradual increases of porosity of