Science of the Total Environment 473–474 (2014) 651–658

Contents lists available at ScienceDirect

Science of the Total Environment

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

The Cartridge Theory: A description of the functioning of horizontal subsurface flow constructed wetlands for wastewater treatment, based on modelling results

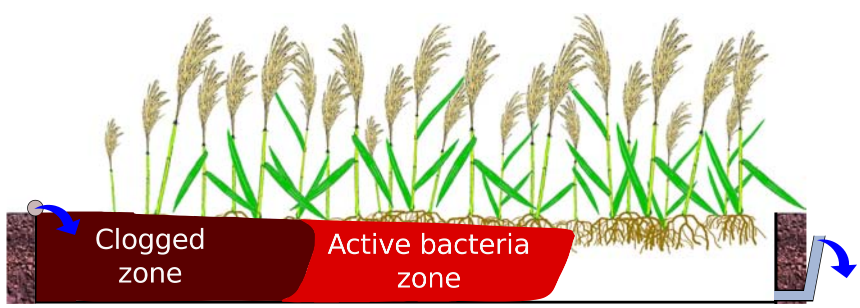
Roger Samsó, Joan García *

GEMMA—Group of Environmental Engineering and Microbiology, Department of Hydraulic, Maritime and Environmental Engineering, Universitat Politècnica de Catalunya-BarcelonaTech, c/Jordi Girona, 1–3, Building D1, E-08034 Barcelona, Spain

HIGHLIGHTS

- This work presents a high-level description of internal wetlands' functioning.
- The presented theory is based on modelling results obtained with BIO_PORE model.
- Growth equations of CWM1 were adapted to comply with population ecology growth models.
- Clogging by inert solids progresses from inlet to outlet with time.
- Clogging hinders bacterial growth and pushes the active bacteria zone towards the outlet.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 17 September 2013
Received in revised form 12 December 2013
Accepted 15 December 2013
Available online xxxx

Keywords:
Wastewater treatment
Bacterial growth
ASM
Solids accumulation
Clogging
Modelling

ABSTRACT

Despite the fact that horizontal subsurface flow constructed wetlands have been in operation for several decades now, there is still no clear understanding of some of their most basic internal functioning patterns. To fill this knowledge gap, on this paper we present what we call "The Cartridge Theory". This theory was derived from simulation results obtained with the BIO_PORE model and explains the functioning of urban wastewater treatment wetlands based on the interaction between bacterial communities and the accumulated solids leading to clogging. In this paper we start by discussing some changes applied to the biokinetic model implemented in BIO_PORE (CWM1) so that the growth of bacterial communities is consistent with a well-known population dynamics models. This discussion, combined with simulation results for a pilot wetland system, led to the introduction of "The Cartridge Theory", which states that the granular media of horizontal subsurface flow wetlands can be assimilated to a generic cartridge which is progressively consumed (clogged) with inert solids from inlet to outlet. Simulations also revealed that bacterial communities are poorly distributed within the system and that their location is not static but changes over time, moving towards the outlet as a consequence of the progressive clogging of the granular media. According to these findings, the life-span of constructed wetlands corresponds to the time when bacterial communities are pushed as much towards the outlet that their biomass is not anymore sufficient to remove the desirable proportion of the influent pollutants.

1. Introduction

Subsurface flow constructed wetlands (SSFCWs) are complex reactors in which different physical, chemical and biochemical reactions take place simultaneously. Nowadays the available knowledge on this

* Corresponding author. Tel.: +34 934016464; fax: +34 934017357.
E-mail address: joan.garcia@upc.edu (J. García).

0048-9697/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.scitotenv.2013.12.070

technology is mostly empirical and very case-specific and for this reason it is very difficult to elucidate which are the most fundamental functioning patterns of these systems. In fact, there is still no clear overall understanding of the interrelations of all processes taking place within them (Kumar and Zhao, 2011; Langergraber, 2007). In our opinion, understanding the basics of the internal functioning of wetlands is a crucial step towards making this technology more efficient, predictable and reliable in the forthcoming years. It will also help us clearly identify and define what we can expect from this technology and decide whether it is the best option in every specific case.

Since the application of numerical models to SSFCWs, they have been seen as a potential tool to brighten the "black box" to which these systems have usually been assimilated. Although most of the available models include equations to simulate a large proportion of the processes that take place within SSFCWs (Langergraber and Šimunek, 2012; Llorens et al., 2011a,b; Mburu et al., 2012; Ojeda et al., 2008; Rousseau, 2005), so far most efforts have been put on matching measured effluent pollutant concentrations and, in general, less attention has been given to describing the internal dynamics of the wetlands. Acknowledging this fact, the BIO_PORE model (Samsó and García, 2013a,b) was developed with the main aim of improving the understanding of SSFCWs' internal functioning, and more specifically on the interrelations between bacterial communities and accumulated solids in the long-term. The BIO_PORE model is the result of combining flow and transport equations together with the biokinetic model Constructed Wetland Model number 1 (CWM1) (Langergraber et al., 2009) within the COMSOL Multiphysics ™ platform, which makes it possible to simulate bacterial growth and pollutants degradation and transformations in wetlands and to make inferences on the real system in which it is applied.

In this paper we introduce what we named "The Cartridge Theory" for horizontal subsurface flow constructed wetlands (HSSFCWs), which is a description of their functioning based on the interaction between accumulated solids (leading to clogging) and bacterial populations. This theory intends to be as generic as possible, and for this reason it presents a simplified and thus ideal perspective of how wetlands function. Generally speaking, this theory assimilates the progressive clogging of HSSFCWs granular media to the consumption of a generic cartridge and was developed from a combination of our practical knowledge on constructed wetlands (CWs), and from the deep understanding of the main treatment processes gained during the development and application of the BIO_PORE model (Samsó and García, 2013a,b).

Since the presented theory is mostly based on simulation results obtained with BIO_PORE model, in this paper we first justify the changes applied to the original formulation of CWM1 so that the resulting growth of bacterial communities is consistent with existing and widely accepted population dynamics models (Verhulst, 1838). We do that by individually studying the evolution of the biomass of a single functional bacterial group (fermenting bacteria) in a specific point near the inlet section of a HSSFCW. This study brings up a discussion of how bacterial communities interact with each other and how they depend on the environmental conditions (e.g. accumulated solids, available space and substrates), which leads us to the final theory for horizontal subsurface-flow constructed wetland functioning, detailed at the end of the paper.

We expect that the current work will not only contribute to improve the way in which dynamics of bacterial communities is described with current mathematical models for CWs, but will also provide a tool (the Cartridge Theory) to explain the most basic functioning patterns of HSSFCWs.

2. Methods

2.1. Model description

In this paper we use the BIO_PORE model to run all simulations. This model was built using Comsol Multiphysics™ and implements fluid flow and transport equations coupled with the biokinetic expressions of Constructed Wetland Model number 1 (CWM1). CWM1 is based on the Activated Sludge Model 1 (ASM1) (Henze et al., 2000) and on the Anaerobic Digestion Model 1 (ADM1) (Batstone et al., 2002) formulations and considers 6 functional bacterial groups: heterotrophic (X_H), nitrifying (X_A), fermenting (X_{FB}), acetotrophic methanogenic (X_{AMB}), acetotrophic sulphate reducing (X_{ASRB}) and sulphide oxidising bacteria (X_{SOB}) (Langergraber et al., 2009). Moreover BIO_PORE is able to describe the fate and transport of the most common pollutants found in urban wastewater, including COD, ammonium and ammonia and nitrite and nitrate and sulphate and dihydrogen sulphide. For details on model equations, main hypothesis and assumptions, calibration and limitations, the reader is referred to Samsó and García (2013a,b). Some of the changes made to the original formulation of CWM1, which affect the particulate fractions of COD are also described in Samsó and García (2013a).

2.2. Pilot system used for simulations

Simulations were run for a pilot wetland with size and features of wetland named C2 in García et al. (2004a, b). This wetland was 10.3 m long and 5.3 m wide, with a bottom slope of 1% and planted with *Phragmites australis*. The granular medium consisted of fine granitic gravel (D_{60} = 3.5 mm, coefficient of uniformity = 1.7, initial porosity n = 40%) with a gravel depth of approximately 0.6 m at the inlet and 0.7 m at the outlet. Water depth was 0.5 m on average. The system was fed with urban wastewater previously treated in an Imhoff tank. Average measured inflow pollutant concentrations, which were used to feed the model, are given later in the text (See Table 1). Notice that although measured effluent pollutant concentrations are available for this system, they are not utilized in the current work, since the comparison of measured data and simulation results was already carried out in Samsó and García (2013a). For a detailed description of the pilot, the reader is referred to Aguirre et al. (2005), García et al. (2007, 2004a,b) and Huang et al. (2005).

2.3. Simulation strategy

Three individual simulations (S1, S2 and S3) were run using incremental versions of the same equation to represent the period comprised between the start-up and the third year of operation of the pilot wetland system. Despite a 3 year period was simulated, the time-scale of the figures presented in the results section was cropped to emphasize only the relevant data.

Initial concentrations of bacteria within the wetland were set to very low values (0.001 mgCOD L^{-1}) for all three simulations to represent start-up conditions. Constant values for hydraulic loading rate (36.6 mm d^{-1}), water temperature (20 °C) and influent pollutant concentrations were used to facilitate interpretation of the model output. Influent pollutant concentrations were extracted from data averages of an experimental study carried out in the pilot wetland by García et al. (2005). The fractioning of the influent COD was made using recommended values for primary effluents in ASM1 (Henze et al., 2000) (Table 1), which is a common practice for all models based on its formulation, since otherwise a very detailed characterisation of the influent wastewater is required. Note that in this system, the influent sulphur concentrations were higher than in average urban wastewaters, since potable water in the metropolitan area of Barcelona is partially obtained from a river that drains a chalk basin (Samsó and García, 2013b).

Plant oxygen release (3gO_2 m^{-2} d^{-1}) and S_{NH} and S_{NO} plant uptake (0.2gN m^{-2} d^{-1} each) were considered to take place only on the top 30 cm of the granular media after the mixing zone (inlet). Plant effects on the hydrodynamics of the wetland were not considered in the current version of the model (Samsó and García, 2013a). Likewise, all sorts of stochastic processes known to take place in wetlands (e.g.