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Nitrification process modeling in intermittent sand filter applied for wastewater treatment

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ABSTRACT

The aim of this study was to propose a nitrification process modeling in an intermittent sand filter (ISF) using the biofilm compartment of Aquatic Systems Simulations (AQUASIM) software and the activated sludge model (ASM1) published by Henze et al. (2000). We verified that the software and the initial modeling of equations were suitable for the nitrification modeling until the hydraulic loading rate of 400 $L\,m^{-2}\,d^{-1}$, organic loading rate of 155.6 $gCOD\,m^{-2}\,d^{-1}$ and nitrogen loading rate of 20.4 $gN\text{-}NH_4^+\text{-}N\,m^{-2}\,d^{-1}$. In order to adapt the modeling for all hydraulic loading rates (HLR) studied, the set of equations was complemented with the inclusion of an F factor. This factor adapts the ASM1 model to the condition of lesser interaction between influent and the biofilm due to hydraulic loading rate increasing. Thus, the AQUASIM software along with the proposed new modeling was able to simulate the process for all HLR ranging from 100 to 800 $L\,m^{-2}\,day^{-1}$.

1. Introduction

Nutrients originated from domestic and industrial sewage can lead to process of eutrophication of water bodies. In addition, the consumption of water rich in nitrates can cause the disease known as blue baby syndrome (nitrate competition for oxygen in the blood), stomach problems in adults and even cancer (EPA, 2007).

The deterioration in water quality resulting from eutrophication is estimated to have already reduced biodiversity in rivers, lakes and wetlands by about one-third globally, with the largest losses in China, Europe, Japan, South Asia and Southern Africa (OECD, 2012).

Regarding sewage treatment, removing nitrogen in sand filter was evaluated by several authors (Darby et al., 1996; Rodgers et al., 2005; Healy et al., 2007; Tonon et al., 2015). All these authors found that this treatment system has great nitrification capacity. Tonon et al. (2015) obtained NH_4^+-N removal efficiency higher than 80% considering hydraulic loading rate from 100 to 500 $L\,m^{-2}\,d^{-1}$, organic loading rates from 38.9 to 194.5 $g\,m^{-2}\,d^{-1}$ and NH_4^+-N loading rate from 5.1 to 25.5 $g\,m^{-2}\,d^{-1}$.

In recent years, mathematical modeling has become popular as a support tool for projects, operation and control of systems used in sewage and effluent treatment. However, since the publication of the activated sludge models (ASM) by Henze et al. (2000) there is still no consensus in relation to a standard model for biofilms (Wichern et al., 2008).

The AQUASIM software is a simulation and data analysis program for aquatic systems described by Reichert (2014). It can be used to calculate substrate removal in biofilm reactors for any specified user of microbial system. It can also calculate the biofilm thickness development over time. However, its major limitation is considering the spatial variation gradients of substrate and microorganisms by the biofilm only in perpendicular direction of the substratum (Wanner and Morgenroth, 2004).

Wanner and Morgenroth (2004) used the kinetics of Benchmark 3 (BM3) (Rittmann et al., 2004) to model the substrate removal and biofilm growth in the biofilm compartment of AQUASIM. Sezerino et al. (2005) modeled the nitrification in sand filter with hydraulic loading rate of 93 $L\,m^{-2}\,day^{-1}$ using the kinetics model of ASM1. Wichern et al. (2008) simulated the elimination of COD and nitrogen in the sand filter using the kinetics model of Activated Sludge Model 3 (ASM3) (Koch et al., 2000) with hydraulic loading rate up to 200 $L\,m^{-2}\,day^{-1}$.

According to Wichern et al. (2008), the quantification of single processes in natural systems such as soil or sand filters is still very difficult due to the inhomogeneity of the substratum. Nevertheless, recent studies show modeling systems such as constructed wetlands using different mathematical tools (Pálfy and Langergraber, 2014; Fournel et al., 2013).

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In this context, this study aims to modeling the nitrification in intermittent sand filters. The nitrification process was chosen because this reactor is known for its high efficiency in this biotransformation, especially at low hydraulic loading rate (HLR).

2. Methodology

As described by De Oliveira Cruz et al. (2013) and Tonon et al. (2015), this project was carried out in a research area of the School of Civil Engineering, Architecture and Urban Design, University of Campinas (UNICAMP), Brazil. The raw wastewater was collected from the wastewater collection network within the campus of the University, with a portion of its flow directed to the anaerobic filters. The operation of the anaerobic filters had up flow and hydraulic retention time of 9 h (De Oliveira Cruz et al., 2013).

2.1. Sand filters

As detailed by Tonon et al. (2015) the effluent from the anaerobic filters was directed onto the surface of four sand filter surfaces. Before hitting the surface of the sand bed, the liquid collided with splash plates consisting of square plates with 0.20 m in length improving the spreading on the bed.

Cylindrical boxes with internal diameter of 1.00 m (superficial sand filter area of 0.79 m^2) were used in the sand filter construction. The bed was composed of three stratified layers starting at the base of the reactor. The first one was 0.20 m depth and consisted of gravel with effective size (D_{10}) of 16.12 mm and uniformity coefficient (UC) of 45.80 ± 0.40%. The second layer consisted of gravel with D_{10} equal to 7.51 mm and UC of 1.66, with a 0.05 m depth. This material served as sand support; thus, preventing the particles drainage (Tonetti et al., 2012).

The sand bed was 0.75 m depth, and the sand used had the effective size of 0.18 mm, uniformity coefficient of 3.18, and empty bed coefficient of 28.6 (0.9)%. To expand the natural aeration of the bed, a vent pipe with internal diameter of 0.050 m and with 0.025 m holes throughout its length was laterally installed in each filter.

The anaerobic filter effluent was loaded from the top of the surfaces of the sand beds in hydraulic loads of 50 L m^{-2}. This value was provided in a particular frequency of application and at short time intervals for each of the four sand filters (SF1, SF2, SF3, SF4) (Table 1).

Raw wastewater and effluent samples from the anaerobic filters and the four sand filters were collected weekly for 134 weeks. This study had to be split in three phases, each of them elapsing over eight months (Table 1). There were occasional stops for wash the filters with clean water and system maintenance. It was collected samples of the effluent leaving the sand filters in the output pipes, after the last daily disposal, when an increase in the outflow was clearly observed (Tonon et al., 2015). Analyzes such as Chemical Oxygen Demand (COD), ammoniacal-N ($NH_4{}^+$-N) and nitrate-N ($NO_3{}^-$N) were performed according to the Standard Methods for the Examination of Water and Wastewater (APHA/AWWA/WEF, 2005).

2.2. Mathematical modeling

Activated Sludge Model – ASM1 (Henze et al., 2000) consists of a set of variables that are calculated using constants provided in the literature. The calculated variables are: $S_{S:}$ readily biodegradable substrate (gCOD m^{-3}); X_{BH}: active heterotrophic biomass (gCOD m^{-3}); X_{BA}: active autotrophic biomass (gCOD m^{-3}); S_O: dissolved oxygen (gO_2 m^{-3}); S_{NO}: nitrate and nitrite nitrogen (gN m^{-3}) and S_{NH}: $NH_4{}^+ + NH_3$ nitrogen (gN m^{-3}). Table 2 shows the stoichiometric and kinetic parameters values at 20 °C, which we used in the study.

The original model equation was presented by Henze et al. (2000) as a matrix. For this study we disregarded anoxic processes, since it is an aerated system. As for the hydrolysis and ammonification we considered that they occurred only in the anaerobic reactor.

The processes considered as well as the variables and the initial stoichiometric coefficients are shown in Table 3. The stoichiometric coefficients of the parameters S_S, X_{BH}, X_{BA}, S_O and S_{NO} were the same presented by Henze et al. (2000). The S_{NH} coefficients were used by Wichern et al. (2008), which showed better performance in this process.

The biofilm compartment of AQUASIM software was used for modeling. The reactor was defined as the confined type with total volume equal to 0.589 m^3. This value was determined by the reactor volume and empty bed volume of the sand used. Only the liquid phase was considered in the pore volume and the biofilm matrix was defined as rigid, that is, without diffusive transport of solids. The biofilm area was considered constant and, therefore, the detachment rate of the biofilm was set as null.

For the determination of the biofilm area we initially used the geometric growth model presented by Wichern et al. (2008) and Mburu et al. (2014). From this model we estimated maximum biofilm thickness prior to filter clogging.

The bed filling material was approached with spheres with the same size that can tap 4–8 points. At these points biomass growth would not be possible. By Eq. (1) we can determine this lost area (A_{loss}) between two spheres. For this, it was related the radius r of the single sphere (r = 0.09 mm), the biofilm thickness (L_F), the number of contacts points per sphere (B = 6), the reactor volume (V = 0.589 m^3) and the number of grains N.

$$A_{loss} = B\pi L_F(2r + 2LF)\left[m^2\right] \quad (1)$$

The value of N was determined according to Eq. (2). In it, the porosity (ε) is equal to 0.286.

$$N = \frac{(1-\varepsilon)V}{\frac{\pi}{6}(2r)^3} \quad (2)$$

The remaining area ($A_{remaining}$) was found from Eq. (3). The maximum thickness of the biofilm determined was 23.74 μm. We decided to adopt a thickness area of approximately 20 μm, in order to avoid bed clogging. We found by Eq. (3) a biofilm area of about 2500 m^2.

$$A_{remainig} = N\pi(2r)^2 - NA_{loss}\left[m^2\right] \quad (3)$$

2.3. Initial conditions, system inputs and simulation

Table 4 shows the values of the initial conditions used. The inputs in the system for the variables S_S, S_{NO} and S_{NH} were calculated by multiplying the initial concentration S_{in} by the daily flow application Q_{in}, where the flow is given by the product of the hydraulic loading rate by the area of the sand filter evaluated (0.79 m^2).

The oxygen input (OI) in the vertical flow bed was obtained following Platzer's guidelines (1999) as a result of diffusion and convection. The diffusion input refers to input of 1 gO_2 m^{-2} h^{-1}. In the case we considered that the process does not occur 1.5 h after each load (Eq. (4)).

$$OI_{diffusion} = 1\left[\frac{gO_2}{(h.m^2)}\right] \times Bedarea\left[m^2\right] \times (24\,[h]$$
$$-1.5\,[h] \times numberofapplications)\left\lfloor\frac{1}{d}\right\rfloor \quad (4)$$