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RESIDENCE TIME DISTRIBUTION AND DISINFECTION OF SECONDARY EFFLUENTS BY INFILTRATION PERCOLATION

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ABSTRACT

Infiltration percolation is used as a tertiary treatment in order to meet the WHO's microbiological standards applying to unrestricted agricultural wastewater reuse. Faecal coliform removal, Δfc, was investigated in laboratory columns and on a 565 m^2 pilot plant. Δfc observed in laboratory columns was shown to be closely related to water detention time distribution, DTD. The relationship between Δfc and DTD, which has been determined from column tests, allowed a good prediction of the disinfection performances of the pilot plant for hydraulic loads of 0.54 and 0.66 m/d. For 0.82 m/d, the maximum load that could be tested on the plant, the mean faecal coliform removal was more than 1 log. unit higher than predicted. These unexpected good performances, though calling for more comprehensive explanation, speak for the widespreading of a reliable and cost-effective extensive technique. © 1999 IAWQ Published by Elsevier Science Ltd. All rights reserved

KEYWORDS

Detention time; disinfection; infiltration percolation; wastewater reuse.

INTRODUCTION

Effluents from conventional wastewater treatment plants cannot be directly used for irrigation of public parks, sports fields, golf courses and edible crops. They have to be disinfected prior to being reused in order to comply with relevant health regulations. When the objective is to meet World Health Organization unrestricted irrigation criteria, the additional treatment can be achieved through infiltration percolation (Bouwer, 1996; Salgot *et al.*, 1996). Infiltration percolation plants are intermittently fed with secondary effluents which percolate through 1.5 to 2 m unsaturated coarse sand and are recovered by underdrains.

Microorganisms are eliminated through numerous physical, physico-chemical and biological interrelated processes. Though WHO's wastewater reuse guidelines do not refer to any virological criterion, health risks related to viruses are of concern. F^+ and CN13 coliphage removal is being investigated (Brissaud *et al.*, 1997). Elimination of helminth eggs was proved to be very effective (Guessab *et al.*, 1993; Peñuelas *et al.*, 1997). Efficiency of faecal coliform removal is the key objective of infiltration percolation. It has been extensively investigated and shown to mainly depend on water detention times in the filtering medium and

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on oxidation effectiveness (Schmitt, 1989; Makni, 1995). Achieving total oxidation requires the oxygen amount needed for organic matter and nitrogen oxidation to be balanced by convective and diffusive oxygen supply. This condition is generally satisfied when infiltration percolation is applied to the treatment of activated sludge effluents (Brissaud *et al.*, 1991). Detention times are related to operating parameters such as the hydraulic load, the number of flooding-drainage cycles per day, f, the feeding rate and preferential pathways. Feeding sand filters with a pivot irrigation system and a proper maintenance of the infiltration surface virtually eliminate short-circuits.

The development of infiltration percolation as a disinfection technique will depend on the hydraulic load that can be treated. Tests were performed on sand columns and pilot plants in order to determine the removal of faecal coliforms that can be expected as a function of the hydraulic load and the daily fractionation of the applied load.

FILTRATION THEORY

The transport of bacteria in a saturated porous medium can be described by equation (1):

$$\partial C/\partial t = D\,\partial^2 C/\partial z^2 - u\,\partial C/\partial z - k_a C + R_d \quad (1)$$

where C is the bacteria water content, D the dispersion coefficient for bacteria, u the pore water velocity, k_a the adsorption rate coefficient and R_d the rate at which bacteria desorb from the stationnary phase (Johnson *et al.*, 1995). Considering every sand particle as a collector, k_a may be expressed as shown below:

$$k_a = 1.5\,(1 - \theta)\,\eta\,u\,z/d_p \quad (2)$$

Where θ is the water content, η the single collector efficiency, z the depth into the sand filter and d_p the sand particle diameter. The single collector efficiency is the sum of efficiencies η_d, η_i, η_g respectively related to molecular diffusion, interception and Van der Waals forces, and sedimentation (Yao *et al.*, 1971). η_d and η_g are proportional to u^{-1}; η_i is equal to 0.5 $(d/d_p)^2$; d is the colloid diameter. Detachment models have been studied by Johnson *et al.* (1995), Bengtsson and Lindqvist (1995).

Assuming steady state conditions, with a constant Co bacteria concentration entering the filter, and neglecting the dispersion effect, the concentration at depth z may be writen as :

$$C/Co = \exp[-1.5\,(1-\theta)\,\alpha\,\eta\,z / d_p] \quad (3)$$

where desorption is represented by an attachment efficiency, α, which can be considered as the ratio of bacteria definitely attached on the stationary phase (solid phase + biofilm) to the number of contacts between suspended bacteria and the stationary phase. Then, bacteria removal, Δfc, in steady state conditions is given by equation (4):

$$\Delta fc = \log (Co/C) = 0.65\,(1-\theta)\,\alpha\,\eta\,z / d_p \quad (4)$$

According to equation (4), bacteria removal is proportional to the depth, z, which is in good agreement with several experiments (Lance *et al.*, 1980). Moreover, assuming η proportional to u^{-1}, Δfc through a sand bed is found to be proportional to t, the water detention time in the bed.

At high rate intermittent infiltration, neglecting dispersion effects is no more acceptable. It will be shown that the only consideration of an average detention time leads to poor predictions of faecal coliform removal. Δfc will be calculated from the water detention time distribution, than can be measured from tracer tests or calculated by numerical models, asuming a linear relationship

$$\Delta fc = a\,t + b \quad (5)$$

between Δfc and detention time, t. Equation (5) differs from the one that could have been deduced from equation (4) by the addition of constant b, which allows taking into account the straining of bacteria at the

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sand bed surface. Predictions of bacteria removal Δfc cannot be successfull if the attachment efficiency, α, is not a constant.

MATERIALS AND METHODS

Column tests

Sand column tests have been performed in order to find out whether the disinfection of secondary effluents is related or not to the distribution of water detention times in the sand bed. Columns, 1.0 m deep, are 0.19 m in diameter, filled with a coarse sand (d_{50} ~ 700 μ, U ~ 6).

Secondary effluents were applied according to a five days operating - two days drying schedule. During the operating phases, the hydraulic load was 0.40 metre per day. The fractionation factor, f, i.e. the number of flooding-drainage cycles per day, was changed every week; it was successively 2, 4, 8 and 12. The application rate was 1.4 x 10^{-4} m/s. Two sets of experiments were performed with two different activated sludge effluents.

Detention time distributions were determined by adding a tracer (NaCl) to the water of one application sequence. The water conductivity and the water rate were monitored at the column outlet. Secondary effluents and the filtrated water were analyzed for SS, COD, NTK, N-NO_3 and faecal coliforms.

For each f value, the quality of the filtrated water was monitored by analyzing the water collected at 6 regular time intervals during one flooding-drainage cycle.

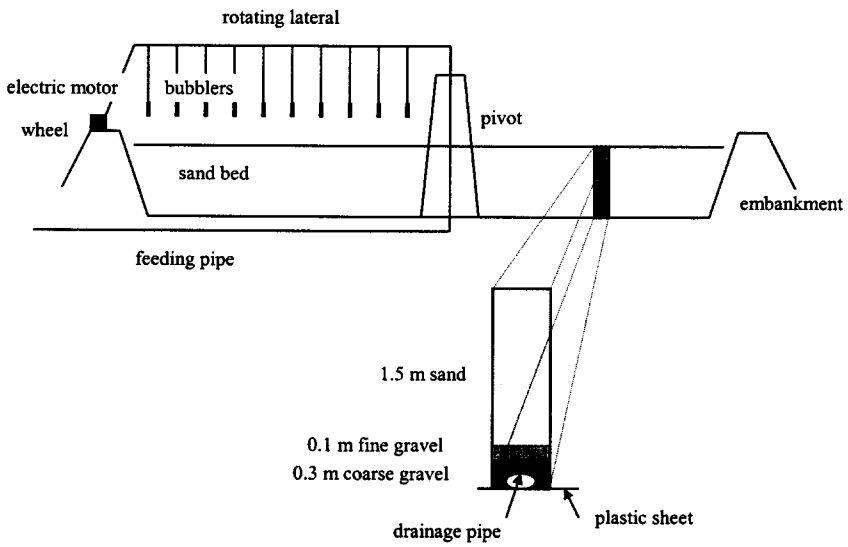

Figure 1. Schematic cross section of an infiltration percolation filter.

Pilot plant tests

Disinfection performances were investigated as a function of hydraulic load in a 565 m^2 pilot infiltration percolation plant. A dune sand (d_{50} ~ 300 μ, U ~ 2.2) filter, 1.5 m deep, was contructed in Vall-Llobrega, Catalonia, Spain (Figure 1). It is fed with activated sludge effluents by a pivot irrigation system. The plant has been operated and monitored since 1992.

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The feeding rate is 20 m^3/hour. Each passage of the pivot lateral delivers a water height of 4.1 cm. A full turn takes 1 hour and 10 minutes. The daily hydraulic load is proportional to the number of the passages of the lateral, which is also the fractionation factor, f. The following hydraulic loads have been investigated (Table 1):

Table 1. Vall Llobrega pilot plant: Hydraulic loads and fractionation factors investigated

f	4	6	8	10	13	16	20
H (m/d)	0.16	0.25	0.33	0.41	0.54	0.66	0.82

Tracer tests have been performed for 0.54, 0.66 and 0.82 hydraulic loads. NaCl was added to secondary effluents applied for one full turn of the lateral. For each load, physico-chemical and microbiological parameters were monitored during a few sequences (a sequence is the duration between two consecutive passages of the lateral). For each sequence, the applied water was sampled at the beginning, middle and end of the feeding sequence; from 15 to 5 samples of the filtered water were collected the same day at regular intervals during one sequence.

RESULTS

Column tests

Distributions of the water detention times are highly influenced by the fractionation of the daily hydraulic load (Fig. 2). When f is only 2, an important part of the applied water spends only a very few hours in the sand bed. Tracer breakthrough at the bottom of the column occurs less than one hour after NaCl application on top of the bed. When f increases up to 4, the shortest residence time is about 6 hours. It reaches 17 hours for f = 12. Such differences in DTD have a considerable impact on disinfection performances, as shown in Fig. 3.

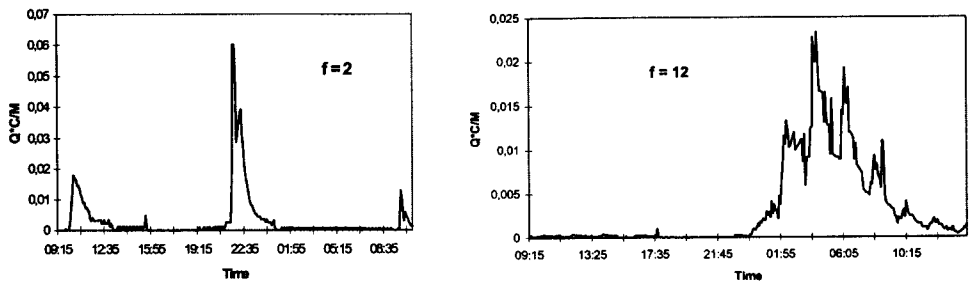

Figure 2. Detention time distribution for f = 2 and 12.

The average quality of secondary effluents and filtered water is shown in Table 2.

Table 2. Quality of secondary effluents and filtered water

	Second. effl.	Filt. Water	Second. effl.	Filt. Water
SS (mg/l)	35		34	
COD (mg O_2/l)	240	21	124	20
NTK (mg:l)	48	2	30	2
N-NO3 (mg/l)		47	2	21
Faec. coli. (CFU/100 ml)	7.3×10^6		6.1×10^5	

Whatever the quality of secondary effluents and the fractionation factor, f, the oxidation of the filtered water was achieved.

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Data obtained from 4 experiments performed on the same column with the same applied secondary effluent are reported in figure 3. The only difference between the experiments is the value of the fractionation factor, f. Figure 3 represents, for each experiment, the faecal coliform content analyzed in the water collected at 6 regular time intervals at the bottom of the column during one flooding-drainage cycle. Faecal coliform removal is shown to be highly dependent on the fractionation of the daily hydraulic load. The mean coliform removal decreases with the f value and, for a given f value, faecal coliform content varies during a flooding-drainage cycle. For most experiments, coliform removal can be explained through DTD analysis.

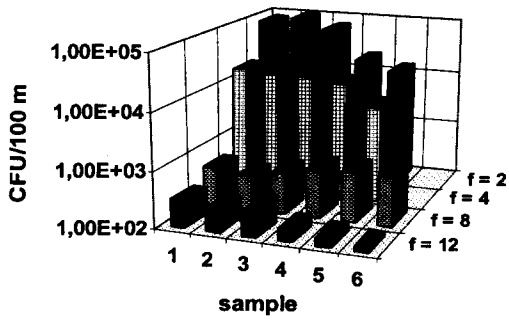

Figure 3. Column tests: faecal coliform removal

When the DTD of the water infiltrated during an application sequence has been determined for a given f value, it is easy to calculate, in each of the 6 samples collected during an application-drainage sequence, the proportions, x_i, of the water applied during each previous sequence (i). Thus, a DTD is calculated for each sample (Bancolé, 1995). For f = 2 and 4, DTD differ from one sample to another; fewer differences are noticed for f = 6 and no significant differences were observed for higher f values.

Then, faecal coliform removals were calculated for each sample, assuming a linear relationship between the water detention time and the faecal coliform removal (equation 5):

$$\Delta fc = - \log_{10} [\Sigma (x_i . 10^{-(ati + b)})] \quad (6)$$

where ti is the time elapsed between the (i) application and the collection of the sample. Coefficients a and b were determined by an autometic least squares fitting procedure applied to the results of 8 experiments. The correlation coefficient between calculated and observed faecal coliforms removals is r = 0.91, which is a fairly high value for microbiological data (Figure 4).

Pilot plant

As shown Table 3, secondary effluents were efficiently oxidized when percolating through the sand bed. Ammonium was completely oxidized to nitrates.

Table 3. Pilot plant: physico-chemical performances

SS (mg/l)		COD (mg/l)		$N\text{-}NH_4$ (mg/l)		$N\text{-}NO_3$ (mg/l)	
Sec. effl.	filt. water	sec. effl.	filt. water	sec. effl.	filt. water	sec. effl.	filt. water
18	1.2	97	51	28	0.5	0.8	27

Observed faecal coliform removals tend to decrease with increasing hydraulic loads, H, for loads ranging between 0.16 and 0.66 m/d (Figure 5). Le lowest value, 2.5, was observed for H = 0.66 m/d, just after a few days break in the functioning of the plant. H is proportional to f and the water height delivered at each passage of the lateral is always only 4.1 cm; the effects are that detention times decrease with increasing

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hydraulic load but without very short detention times (Figure 6). So, high H values do not mean very low coliform removals.

In 1997, a 0.82 m/d hydraulic load was applied for more than 6 months. Data obtained during this period did not confirm the decrease of Δfc with increasing hydraulic loads (Fig. 5). The mean Δfc value measured over the 6 months period was 4 log. units.

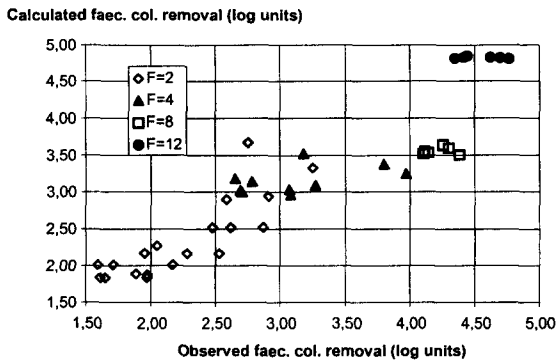

Figure 4. Modeling faecal coliform removal as a function of detention time ($\Delta fc = 0.2\ t + 1.0$ with t expressed in hours).

Faecal coliform removal was calculated for H = 0.54, 0.66 and 0.82 m/d, using the DTD determined by tracer tests and the linear relationship between Δfc and the detention time derived from column tests. Calculated Δfc are respectively 3.4, 3.3 and 2.8. Though the granulometry of the sand was not the same in columns and in the pilot plant, Δfc predicted values were in a very good agreement with the observed data. For H = 0.82 m/d, measured performances are far better than predicted. Surprisingly high performances and variations of Δfc for a given hydraulic load show that the consideration of detention time distribution cannot always explain bacteria removal by infiltration percolation.

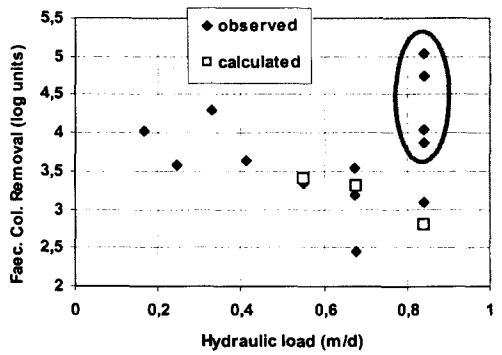

Figure 5. Faecal coliform removal as a function of the hydraulic load.

Faecal coliform removal must be interpreted in a more spohisticated manner than as a simple detention time dependent relationship. Straining efficiency at the bed surface may change over years. Moreover, attachment efficiency, α, may not be constant. This parameter is related to the die-off rate of bacteria; actually; dead bacteria are no longer in the flow. There are reasons to think that bacteria die-off and, therefore, α are related, through the endogenous respiration, to the oxidation process of the dissolved organic matter which percolates into the sand filter. A better understanding of the disinfection performances requires a precise

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monitoring of the oxidation process along the soil profile. The vertical distribution of the oxidation rate is fluctuating with the COD of the applied wastewater, the hydraulic load and the filter operation schedule.

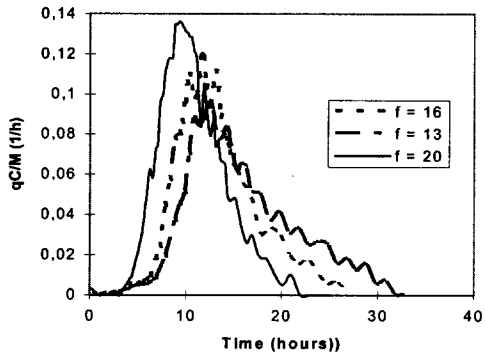

Figure 6. Vall Llobrega pilot plant: detention time distributions.

CONCLUSION

Infiltration percolation allows oxidizing and disinfecting wastewaters. This is the reason why this technique is used, in Spain and France, as a tertiary treatment with the aim of removing pathogen microorganisms from the effluents of conventional wastewater treatment plants. It is a low-technology method that can be used to prepare wastewater for unrestricted irrigations.

Disinfection performances provided by infiltration percolation facilities are uneven. The main part of the variability of faecal coliform removal is explained by the water detention times. A linear relationship between Δfc and the water detention time and experimental determination of detention time distribution through tracer tests allowed a fair modeling of experiments performed on laboratory columns. Moreover, the same relationship and measured detention time distributions led to predictions of disinfection performances fitting the data observed in Vall-Llobrega pilot plant. Therefore, disinfection performances can be predicted by numerical models simulating dispersive transfers in non saturated porous media.

Some removal data, better than predicted by the model, showed that disinfection mechanisms are not well known and have to be more deeply investigated.

Whatever the conclusions of forthcoming experiments, results already available support the spreading of infiltration percolation over Spain and neighbouring countries as a disinfection technique able to meet two main purposes: providing water for unrestricted reuse and protecting the microbiological quality of bathing waters.

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